Industrial Energy Use and Improvement Potential

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INDUSTRIAL ENERGY USE AND IMPROVEMENT POTENTIAL

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Signed ....

Note to readers:

The work conducted in relation to Chapter 7, specifically in reference to the Cement subsector (section 7.2), was in part based on an internal, unpublished, report co-authored by Paul Griffin. The author of the thesis would like to acknowledge the contribution of Paul Griffin, particularly in finding and collating some of the data utilised in the analysis.

ABSTRACT

This thesis aims to examine energy demand within UK industry and assess the improvement potential available through efficiency measures. The techniques employed throughout the work have been mainly engineering based, drawing on thermodynamics. Alongside this approach, an assessment of drivers and barriers to the technical potential was undertaken.

Data availability was a key challenge in the current work. The variety in energy uses meant the use of publically available datasets was limited. A database was constructed utilising site level emissions data, and employed a subsector disaggregation that facilitated energy analysis. The database was used for an analysis of waste heat recovery options. Opportunities were identified in low temperature recovery, heat-to-power technology, and the transport of heat. Each of these options would require further research and support to be fully realised.

It was found that splitting the industrial sector into an energy-intensive and non-energy-intensive subsector, where the grouping was based on the drivers to energy efficiency, allowed generalisations to be made regarding future improvement potential. Based on analysis of past trends, it was found that the energy-intensive subsector has limited potential for further efficiency gains through currently used processes. To make significant improvements radical changes in current processes will be required. A study of the energy-intensive Cement subsector concurred with these findings. Future efficiency improvements in this subsector are likely limited without a shift to alternative cement production.

The non-energy-intensive subsector was thought to have relatively greater improvement potential through existing processes. The analysis of these processes is limited by lack of data however. An analysis of the non-energy-intensive Food and drink subsector therefore focussed on improvements in supplying low temperature heat, rather than the efficiency of specific processes. Opportunities through improving steam systems, increasing combined heat-and-power use, and the adoption of heat pumps were found to offer similar improvement potentials.

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Finally thanks to family and friends, who have provided valuable moral support throughout the process.

"We can only see a short distance ahead, but we can see plenty that needs to be done."

Alan Turing

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LIST OF ABBREVIATIONS

ABI/ABS	Annual Business Inquiry/ Survey
ACEEE/ECEEE	American/ European Council for an Energy Efficient Economy
AD	Anaerobic Digestion
ASD/VSD	Adjustable/ Variable Speed Drive
BAT	Best Available Technology
BAU	Business-As-Usual
BERR	Department for Business Enterprise and Regulatory Reform (replaced by Department for Business, Innovation and Skills, energy and climate change activities now superseded by DECC)
BIS	Department for Business, Innovation and Skills
BOF	Basic Oxygen Furnace
CCA	Climate Change Agreement
CCC	Committee on Climate Change
CCGT	Combined Cycle Gas Turbine
CCHP	Combined Cooling, Heat and Power (also known as Trigeneration)
CCL	Climate Change Levy
CCS	Carbon Capture and Storage
CFP	Carbon Floor Price
CHP	Combined Heat and Power (also known as Cogeneration)
CO_2	Carbon Dioxide
COP	Coefficient of Performance
CRC	Carbon Reduction Commitment
CSI	Cement Sustainability Initiative
DECC	Department of Energy and Climate Change
DEFRA	Department for Environment, Food and Rural Affairs
DTI	Department for Trade and Industry (replaced by BERR)
DUKES	Digest of United Kingdom Energy Statistics
EA	Environment Agency
EAF	Electric Arc Furnace

EC	European Commission
ECRA	European Cement Research Academy
ECUK	Energy Consumption in the UK
EE	Energy Efficiency
EEDS	Energy Efficiency Demonstration Scheme
EI	Energy-intensive
EU	European Union
EU ETS	European Union Emissions Trading System
FDF	Food and Drink Federation
GCV	Gross Calorific Value
GDP	Gross Domestic Product
GER	Gross Energy Requirement
GHG	Greenhouse gas
GQCHP	Good Quality Combined Heat and Power
GVA	Gross Value Added
IDA	Index Decomposition Analysis
IEA	International Energy Agency
IFIAS	International Federation of Institutes for Advanced Studies
I-O	Input-output
IPCC	Intergovernmental Panel on Climate Change
IPPC	Integrated Pollution Prevention and Control
LCA	Lifecycle Assessment
LMDI	Log Mean Divisia Index
LPG	Liquefied Petroleum Gas
MTP	Market Transformation Programme
NAP	National Allocation Plan
NCV	Net Calorific Value
NEDO	New Energy and Industrial Technology Development Organization
NEI	Non-energy-intensive
NPV	Net Present Value
OECD	Organisation for Economic Co-operation and Development
ONS	Office of National Statistics

OPC	Ordinary Portland Cement
ORC	Organic Rankine Cycle
PA	Process Analysis
PI	Purchases Inquiry
PRODCOM	Products of the European Community
QEP	Quarterly Energy Prices
R&D	Research and Development
RD&D	Research, Demonstration and Development
RHI	Renewable Heat Incentive
SDA	Structural Decomposition Analysis
SEA	Statistical Energy Analysis
SEC	Specific Energy Consumption
SIC	Standard Industrial Classification
SME	Small and Medium sized Enterprise
SSI	Sahaviriya Steel Industries
UK	United Kingdom
UN	United Nations
US/ USA	United States of America
US DOE	United States Department of Energy
VoP/VP	Value of Production

CHAPTER 1

INTRODUCTION

Modern lifestyles in developed countries demand vast amounts of energy. This energy is used to maintain the comfort and lighting of our environment, cook our food, provide transport, communicate with each other, keep us entertained and provide a wealth of services on a worldwide scale. Energy can be required directly for these purposes and also in the manufacture of almost everything related to providing the services. The majority of energy demand is currently provided by fossil fuels (IEA 2010b). There are two widely held concerns surrounding this reliance on fossil fuels: their finite nature, and their environmental impact.

As long ago as the nineteenth century Jevons predicted the exhaustion of Britain's coal reserves (Jevons 1866) and today the imminent end of cheap, accessible fossil fuel reserves are recognised as a worldwide concern. As fossil fuels become scarcer and more difficult to extract from the earth their price increases. Linked to the scarcity of fossil fuels are their uneven global distribution, this leads to fears regarding the reliance between nations on imports of energy, and the security of an energy supply that has become vital in maintaining modern standards of living.

Energy is most commonly released from fossil fuels by combustion. During this process carbon in the fuel combines with oxygen in the surroundings to form carbon dioxide[1]. Carbon dioxide (CO_2) is a so called greenhouse gas (GHGs). GHGs act to trap infra-red radiation from the earth's surface in the atmosphere. This is a natural phenomenon without which the earth would be too cold for human life, an increase in the concentration of these GHGs is thought to lead to an unnatural warming of the planet however (Boyle et al. 2003). The Intergovernmental Panel on Climate Change (IPCC) is the leading international body assessing climate change, aiming to represent a clear and unbiased scientific view of the matter. Its reports are drawn on here as evidence for an issue that has been the subject of some dispute. The concentration of CO_2 in the atmosphere has increased from a pre-industrial value of 280 parts per million (ppm) to 379ppm in 2005 (IPCC 2007), these levels far exceed the natural variation seen in the last 650,000 years. The primary source of this increased CO_2 concentration is fossil fuel use (IPCC 2007). Over the twentieth century global average surface temperature increased by about 0.6°C, from 1955-2005 the warming trend was 0.13°C per decade, over twice the mean rate during the twentieth century (IPCC 2007). The period 1995 to 2006 contained eleven of the twelve warmest years on record to 2007 (IPCC 2007). It is *'very likely'* that the observed increase in temperatures is caused by the recorded increase of GHGs (IPCC 2007). Effects emanating from these increased temperatures are likely to

[1] Other substances that can also have environmental effects may also be formed. The focus here is on carbon dioxide, which is the main anthropogenic emitted GHG.

include a loss of polar ice, increasing sea levels, changing regional climatic conditions, and extreme weather events (IPCC 2007). All these effects are likely to accelerate unless the rise in the concentration of GHGs in the earth's atmosphere is halted. The IPCC has suggested that limiting warming to 2°C by 2100 would form a sensible target. This would necessitate a stabilisation of 450ppm of CO_2 (IPCC 2007) in the atmosphere, which would require a considerable reduction in CO_2 emissions from current levels. At least a 50% cut in world GHG emissions is thought to be required by 2050 to reach this target (Committee on Climate Change 2008).

1.1 THE UK MANUFACTURING SECTOR

Climate change and energy resource depletion are worldwide concerns. Although there has been some progress in reaching international agreements on these matters, most notably the Kyoto protocol (with 37 nations committing to a reduction in the emission of GHGs), the consensus required by all nations in forming such an agreement often means progress is slow. It has often fallen to nations (or regional groups, such as the European Union) to impose independent targets that govern their energy use and emissions. The UK has adopted a challenging long term target of an 80% reduction in greenhouse gas emissions by 2050 compared to 1990 levels on the recommendation of the Committee on Climate Change (2008). This was put into law by the UK Climate Change Act 2008 (HM Government 2008). The UK was responsible for 1.6% of world CO_2 emissions from fuel consumption in 2009 (IEA 2011).

The industrial sector is a major contributor to world energy demand and CO_2 emissions. In 2005 the sector accounted for almost one-third of world primary energy use and approximately 25% of world energy and process-related carbon dioxide emissions (IEA 2010a). Whilst high growth in production and corresponding energy use has been seen in developing economies, such as India and China [with China being responsible for 80% of worldwide growth in industrial production over the past twenty-five years (IEA 2010a)], the UK has seen a reduction in industrial energy use whilst continuing to increase output in economic terms (Dyer et al. 2008). Despite this improvement in the energy intensity (energy use per unit of economic output) of UK manufacturing, considerable reductions in the sector's carbon emissions are still required. In 2010 industrial GHG emissions represented approximately a quarter of the UK's total emissions, a reduction in emissions from industry of approximately 70% will be required to reach economy-wide targets (HM Government 2011). If historical growth of the sector continues, then a range of options will be required, including decreased energy intensity, through fuel switching and improved efficiency; the widespread use of alternative fuels, including bioenergy and the electrification of processes (assuming a decarbonisation of the electricity sector); and the use of carbon capture and storage (CCS) technology (HM Government 2011). Progress in reducing emissions has the potential not just to influence industry in the UK, but the application of low carbon technology throughout the world can be accelerated by successful applications in Britain through the transfer of technology to other nations.

1.2 THE ROLE OF EFFICIENCY

Improving efficiency is a vital component of emissions reduction in industry. Whilst there are different definitions of energy efficiency that can be employed (and are discussed later in this work) the energy demand per unit of output (often referred to as the energy intensity when output is economic, or specific energy consumption when output is physical) is adopted for the current discussion. In this context improving energy efficiency can therefore cover a number of energy reducing options including fuel switching, improved process control, and increasing the thermodynamic efficiency of specific processes involved in production. In contrast to other options for reducing emissions, energy efficiency is often technically and economically viable under current conditions. Efficiency is therefore often favoured as the first step in reducing emissions, before aiming to meet the reduced energy demand in a low carbon manner (House of Commons Environmental Audit Committee 1999, Stern 2007, The Institution of Engineering and Technology 2007). Reducing emissions over the long-term is important, but the speed at which this reduction is made also influences the total level of GHGs in the environment. Carbon dioxide has a residence time in the atmosphere of between five and two hundred years[2] (IPCC 2001), and so the cumulative emissions up to the 2050 are more important than the final target. This has led to the adoption of intermediary targets to support the UK's commitment to an 80% reduction by 2050, known as carbon budgets. By 2023-2027 a cut in emissions of 50% from 1990 levels has been adopted (Committee on Climate Change 2012). A significant contribution from bioenergy, electricity decarbonisation and industrial CCS will require considerable research and development and turnover of capital stock. There is an inertia to this form of change (Jollands et al. 2010) and whilst in the long term these options will likely be very important, efficiency measures can have a more immediate impact. Additionally a reduction in energy demand through efficiency reduces the challenge of meeting this demand through alternative means (although conversely it can negatively affect the impact and economics of a scheme such as CCS). The UK's Carbon Plan (HM Government 2011) suggests that if historical growth of the industrial sector continues output will increase by 30% by 2050. To reach sector decarbonisation targets energy demand would need to fall by a quarter alongside increased use of bioenergy, electrification and CCS technologies. Given the expected increased output levels and reduced demand a fall in energy intensity of 40% would be required (HM Government 2011).

[2] No single lifetime can be defined for CO_2 because of the different rates of uptake by different removal processes (IPCC 2001).

1.3 AIMS, CHALLENGES, SCOPE AND APPROACH

The aim of this thesis is to assess the current state of energy use in the industrial sector and the prospects for reducing this energy use. This is a broad aim and the challenges related to this need to be discussed in order to determine the scope of the work and hence the approach taken. This then informs an achievable list of objectives for the thesis. The scope and objectives were set by initial research conducted as part of the thesis.

The main challenges to fulfilling the aim of this work were the variation of energy use within the sector and linked to this the limitation of high quality data regarding energy use and related factors. Fig. 1-1 shows how energy demand varies by both subsector and end use throughout the manufacturing sector. As an example of this variation, within the Basic metals subsector energy demand is dominated by high temperature processes, whereas space heating fulfils a significant proportion of demand in the Electronics and Vehicles subsectors. The Chemicals subsector demands energy in each of the end use classifications. Assessing the energy saving prospects for each of these subsectors therefore necessitates a tailored approach, it would be difficult to apply findings from one subsector widely to another. Fig. 1-1 also hides a considerable amount of detail. The end uses of energy shown themselves cover a wide variation, specifically relating to heat processing, with various types of furnaces, kilns, ovens, steam systems and electrolysis being used. Similarly the subsectors defined in Fig. 1-1 include subsectors that make significantly different uses of energy. An indication of the substantial variation within industry is provided by a study from Future Energy Solutions and the Carbon Consortium (2005), which identified approximately 350 separate combinations of subsectors, devices and technologies for carbon reduction in UK industry. This variation throughout the sector indicates that a broad approach to estimating energy and carbon saving potential would be of limited use.

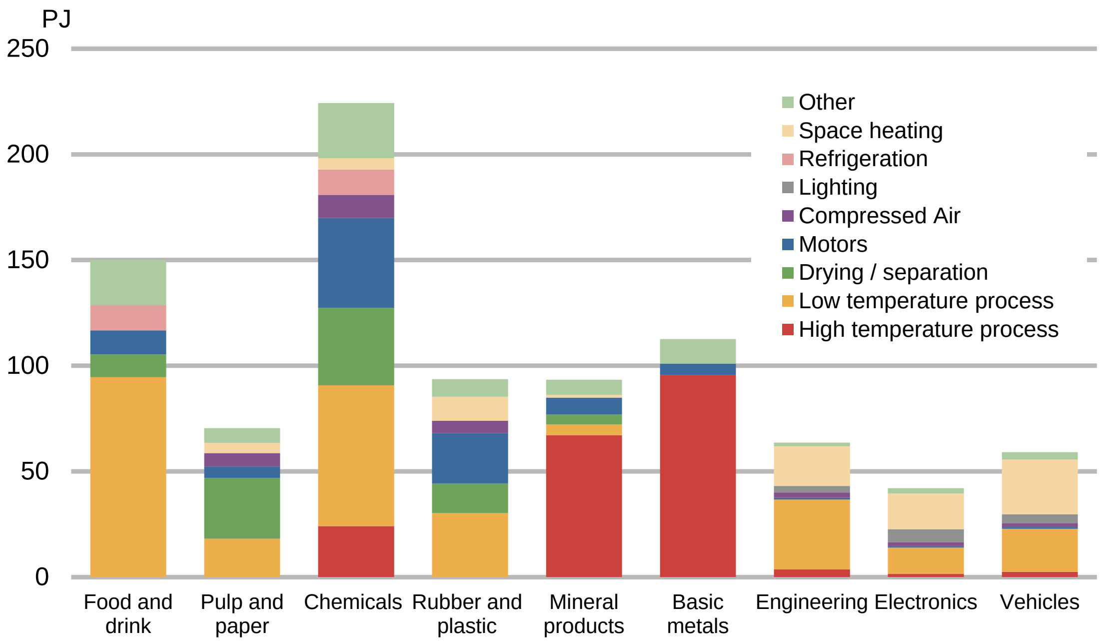

Fig. 1-1: Final energy demand by subsector and end use, UK 2007 (DECC 2009d).

The variation between subsectors and end uses limits the value of statistics regarding energy use in industry. To collect statistical data for industry at the level of disaggregation to fulfil the requirements of the energy analyst is very difficult. This lack of high quality data on energy use within industry is recognised at the international level (Jollands et al. 2010). Available data subsequently tends to involve the aggregation of varied subsectors and uses (as in Fig. 1-1 above), or suffer from accuracy concerns. This situation leads to the reliance on alternative forms of information and case studies for detailed energy use information, this comes with its own challenges. Information collected from a range of different sources can use different conventions making it difficult to combine and contrast disparate studies. There is also an issue regarding commercial confidentiality, with companies concerned that making their energy use data available could harm them competitively. Data can therefore be difficult to obtain at the site level and companies are often reluctant to engage with academia. Energy-intensive companies, who generally place high importance on their energy use, often give substantial resources towards managing this energy use in-house. At the other end of the scale non-energy-intensive companies can have poor knowledge of their energy use and pay it little attention.

There are broadly two approaches to modelling the industrial sector, top-down and bottom-up, as illustrated in Fig. 1-2, these approaches are a consequence of the variation of energy use throughout industry A top-down approach splits industry into subsectors, usually based on available statistical data, and uses this data to undertake an analysis of energy use. This can be useful for assessing current energy use and past trends and has the advantage of covering a large proportion of energy demand. This approach is limited by the disaggregation available from industry-wide statistical sources and means that the conclusions that can be drawn from top-down studies are generally only indicative in nature. There are certain technologies that are used in a large proportion of industry, an assessment of the prospects for these using a top-down study can be valuable. A bottom-up approach, by contrast, would typically focus on a single subsector of industry and disaggregate the energy demand specified by industry wide statistical datasets by further separating energy use into subsectors, processes and manufacturing plants. The data used for a bottom-up study will come from more specific information sources such as trade associations, company reports, and case studies. Whilst a bottom-up study can therefore be useful in terms of presenting higher accuracy findings it will be limited in the breadth of its application, due to its focus. In some cases findings from a bottom-up study can be applied more broadly.

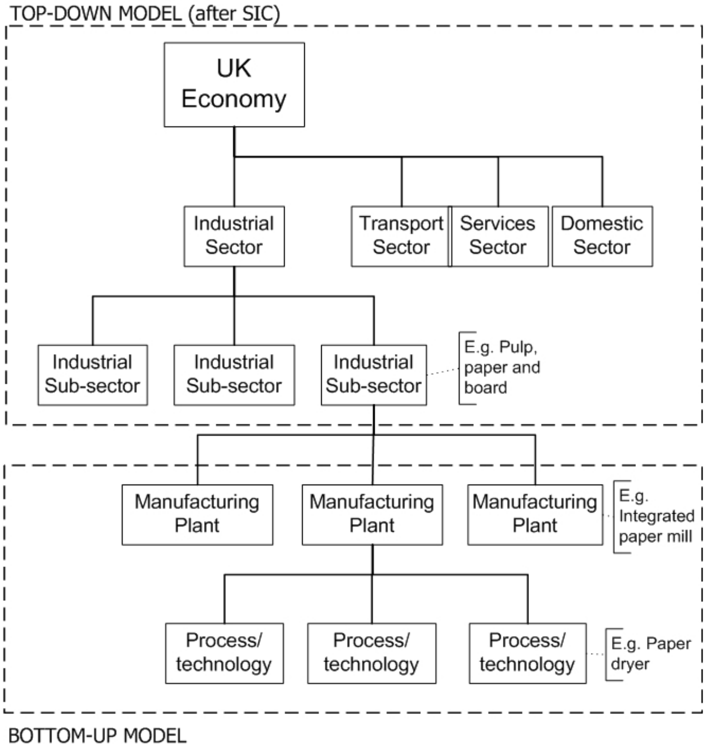

Fig. 1-2: Top-down and bottom-up model schematic [adapted from Dyer et al. (2007)].

Taking the above considerations into account the scope of the work is as follows:

- The work is confined to the manufacturing sector of the UK. This is defined by Standard Industrial Classification (SIC 2003) code as 15-37, not including 23. Chapter 2 provides a fuller description of this classification. The phrases manufacturing and industry are used interchangeably to represent this coverage, other sources may include such subsectors as construction, mining and quarrying (SIC codes 45 and 13 and 14 respectively) within the industrial classification (DECC 2011b). The energy use of these subsectors is fundamentally different to that within manufacturing as defined here however.
- The concern of the work is the reduction of energy demand and related carbon emissions through energy efficiency improvements. Where the prospects for energy efficiency are limited, the discussion may be extended to consider other measures for reducing carbon emissions.
- The approach taken will be mainly engineering based, focussing on thermodynamic and technical issues. However consideration will be given to economic, environmental, legislative and social factors where possible and when considered complimentary to the engineering analysis.
- The final energy demand of manufacturing is the focal point of this work, this is fully defined in Chapter 2. Methods to reduce primary energy demand and carbon emissions that result from changes to the energy supply and transformation sector (primarily within electricity generation) are not analysed, although the effect of expected changes on the carbon emissions from manufacturing may be discussed. The exception to this is when a potential

occurs to generate electricity on-site through process waste, or combined heat and power generation can be used at the site level to reduce the primary energy demand in comparison to a site level heat supply (often a boiler) and central electricity generation.

- Direct energy use within industry is the focal point of the work. Indirect energy demand is not explicitly considered, neither are environmental effects other than the carbon emissions linked to direct energy use. This is discussed further within section 2.2.
- The work will focus on uses of energy that are exclusive to the industrial sector, space heating, lighting and transport will not be discussed as they are well covered by studies on other sectors of the economy.
- The economic demand for a product can have considerable influence on the associated energy use in manufacturing. Although the influence of demand is considered in this work, methods for influencing the demand are considered outside the scope. Demand can be influenced not only by economic growth but also product substitution where a less energy and/or carbon intensive alternative is favoured.

The approach to the thesis is to first carry out analysis in a top-down manner, using available data to understand the current state of energy use within industry and to assess the prospects for technologies that have a wide application. More detailed studies of technologies and subsectors will then be undertaken using a more bottom-up approach. The choice of these studies will be determined by their importance to the industrial sector's energy use and emissions, the existence of similar studies and the availability of data.

An additional consideration in the approach to the work was the sponsorship of the PhD studentship by Great Western Research (GWR). As part of the studentship it was necessary for the two supervisors for the work to be from different institutions and disciplines. The primary supervisor of the work was Geoff Hammond, a Professor of Mechanical Engineering at the University of Bath; the secondary supervisor was Catherine Mitchell, a Professor of Energy Policy at the University of Exeter. This led to an approach that considered the potential for energy efficiency primarily from an engineering (thermodynamic) perspective, but with attention also given to energy policy and other aspects. GWR are based in the South West region of the UK. This influenced the choice of subsectors studied during in the work, the Food and drink subsector is a priority group for the South West Regional Development Agency. GWR organised conferences to bring together their students and also required annual progress reports during the period of the PhD.

1.4 OBJECTIVES AND STRUCTURE OF THE THESIS

The overall aim of the thesis, taking into consideration the scope and approach to the work, is broken down into the following objectives, each of these objectives is focussed on industrial energy and will be dealt with by the following chapters (as highlighted):

1. To assess the different methods of defining and measuring energy efficiency (Chapter 2).
2. To review thermodynamic, engineering and economic techniques and their application to industrial energy use (Chapter 2).
3. To examine the drivers and barriers to improving energy efficiency and the way in which current policy influences these. Furthermore to assess the way these drivers and barriers vary throughout the sector (Chapter 4).
4. To determine the best dataset for assessing the manufacturing sector in a top-down manner and to use such a dataset to examine broad options for decreasing energy use and carbon emissions (Chapter 2, Chapter 3).
5. To assess the historic trends in energy-related GHG emissions and the underlying causes of observed changes (Chapter 5).
6. To perform a detailed study of technologies that have wide application and promising prospects for improving energy efficiency (Chapter 6).
7. To examine subsectors of industry in terms of specific prospects for improving efficiency (Chapter 7).
8. To combine different studies and approaches to assess the overall prospects for improved energy efficiency in manufacturing. Also to assess the different approaches in achieving this objective (Chapter 8).

These objectives are met by a number of separate but interlinked studies, discussions and analyses. Chapter 2 discusses the analysis techniques and datasets used throughout the work. Chapter 3 introduces a database based on site level emissions data and utilises this in a thermodynamic assessment of the UK industrial sector, and in estimating the improvement potential offered through a number of cross-cutting technologies. Chapter 4 examines the drivers and barriers to utilising energy efficient technology in the industrial sector, and the use and effectiveness of policy in the UK in influencing these drivers and barriers. The chapter also splits the sector into two subsectors based on the strength of drivers to energy efficiency. Chapter 5 undertakes a decomposition analysis of historical energy-related carbon emissions from UK industry to assess the underlying reasons for changes in these emissions. Chapter 6 assesses the potential for waste heat recovery technologies throughout the industrial sector. Chapter 7 examines energy use and improvement potential within the Food and drink subsector and the Cement subsector. An overall discussion is included in Chapter 8. Concluding remarks and recommendations for future work are covered in Chapter 9.

There have been a number of publications relating to the work included in this thesis. These are referred to where relevant and are reproduced in Appendix 6.

CHAPTER 2

ANALYSIS TECHNIQUES

Energy efficiency was identified as a focus of the work in the introductory chapter. How to measure energy efficiency is important, both in defining current performance and when assessing improvement potential offered through various technologies. Defining energy efficiency in broad terms is relatively simple, equation (2-1) is generally accepted in this regard (Patterson 1996).

$$\text{Energy efficiency} = \frac{\text{Useful output of a process}}{\text{Energy input to a process}} \qquad (2\text{-}1)$$

The concept of efficiency is easy enough to understand in this basic form. If you can get more useful output for the same energy input; or use less energy input to get the same useful output, then energy efficiency is improving. The difficulty comes when specifying the energy input and the useful output. How these measures are defined will vary dependent on the aim of the study (for example to save money or to reduce emissions). The level at which efficiency is being measured is also important. Measuring the efficiency of a motor is a quite different problem to measuring the efficiency of the whole manufacturing sector. Another consideration is data availability, it may not be possible to use the preferred method for measuring energy efficiency if information on the input and output is not available in the required form. Each of these issues is addressed within the current chapter.

Thermodynamics is the science of energy and forms a basis for energy analysis. The relevant thermodynamic concepts important to the current work are first examined here. They lay a sound scientific basis on which to build further discussion. How energy input is measured in the current work and the use of relevant datasets is then discussed. Energy input is combined with output measures to form efficiency indicators, these are discussed with reference to the practicalities of using different measures of output, including the data availability. Additional techniques for assessing improvement potential within industry include economic techniques, qualitative considerations and interdisciplinary techniques, these are also discussed briefly in the current chapter.

2.1 THERMODYNAMIC ASSESSMENT

Key to the current work are the first and second laws of thermodynamics. The first law is concerned with the conservation of energy. Energy cannot be created or destroyed, only changed from one form to another. Therefore in any process the total amount of energy does not change and the sum of energy input, minus the energy output is equal to the change in energy content of the system under investigation (Cengel and Boles 2002):

$$H_{in} - H_{out} = \Delta H \tag{2-2}$$

where *H* is enthalpy, as defined below.

The second law of thermodynamics introduces the concept of energy having a quality as well as a quantity. All real processes occur in the direction of decreasing quality of energy (Cengel and Boles 2002). This leads to an increase in entropy. The quality, in thermodynamic terms, assigned to a given form of energy is a measure of its ability to perform mechanical work. This is as all energy in the form of mechanical work can be converted to heat, through dissipative processes such as friction. However all energy in the form of heat cannot be converted to mechanical work, even under unrealistic, ideal conditions. This concept leads to the idea of exergy, which is discussed in section 2.1.4 below.

The discussion here focuses on macroscopic, or classical, thermodynamics and does not require knowledge of what is occurring to particles at a microscopic level. The following is not intended to be thorough discussion of what is a complex and extensive subject, but rather an introduction to the aspects that are important to the current work. Consequently for a fuller understanding of the concepts and definitions presented here the reader is directed towards more extensive literature on the subject [for example Bejan et al. (1996), Cengel and Boles (2002)].

2.1.1 Enthalpy

The most commonly used measure of energy found in statistics and analysis is enthalpy, which is a measure of the heat content of a system such that (Cengel and Boles 2002):

$$H = U + pV \tag{2-3}$$

Where *H* is the change in heat content, or enthalpy, of the system; *U* is the change in internal energy of the system, *p* is the pressure of the system and *V* the change in volume. In any study at a level above that of an individual process volume changes are trivial, if they exist at all. Enthalpy can therefore be used in place of the idea of energy content (or internal energy), it is generally more easily understood as a concept (Slesser 1978). Where energy is referred to without any further qualification in this work it will refer to the enthalpy content. As enthalpy is the heat content of a system it should be defined relative to a reference state. Common practice is for this reference state to be 25°C and 1bar (Bejan et al. 1996). Often it is the change in enthalpy that is considered in a study, in which case the reference state is not important.

There are different measures of the enthalpy content of a fuel. The enthalpy content can be measured in terms of the gross calorific value (GCV) or net calorific value (NCV)[3]. The difference between these two measures is that GCV includes the energy required to evaporate water both in the fuel and formed during the combustion process (known as the latent heat of evaporation), NCV excludes this energy. The GCV implies water in the products of combustion is in liquid form, whilst the NCV implies the water in the products is in vapour form (Cengel and Boles 2002). The greater the hydrogen or water content in the fuel the greater the difference between GCV and NCV. The choice of which measure to use is dependent on the aim of the study, data availability and personal preference. The GCV is the best representation of the calorific value (CV) of the fuel under laboratory conditions (AEA 2010a), better reflects process inefficiencies (Phylipsen et al. 1997), and technological advances (DTI 2005a). Conversely NCV corresponds better to the CV in typical real world conditions (AEA 2010a) and is more appropriate when considering environmental concerns brought about by fuel use (DTI 2005a). The Kyoto agreements were based on NCV and NCV is reported more widely worldwide, being utilised in IEA, UN and Eurostat data. The Department of Trade and Industry (DTI, now DECC) recently considered changing figures in its publications concerning UK energy statistics from GCV to NCV (DTI 2005a). After examining the advantages of each method it was decided to maintain the practice in publishing statistics in terms of GCV. Conversion factors for fuels will vary between countries due to commodity quality, for the UK factors are available from DECC (2009a). GCV will be used in the current work, unless stated otherwise, as it is the measure published in the majority of the datasets utilised. Based on the above discussion it is also a better measure when examining energy efficiency.

2.1.2 First law efficiency

The first law of thermodynamics states that energy is conserved, therefore assuming no energy is stored in the system under investigation [$\Delta H = 0$ in equation (2-2)] the sum of energy inputs to a system are equal to the sum of the outputs. However not all of these outputs from a system will be useful, or desired outputs. Consider the simple example of an electrical motor, as shown in Fig. 2-1. 100MJ of electricity is input to the motor, 85MJ of this is converted to mechanical work, whilst 15MJ is converted to heat, primarily through friction and in the windings of the motor. Therefore the first law of thermodynamics is satisfied, the sum of the inputs (electricity) is equal to the sum of the outputs (mechanical work and heat). Only the 85MJ of mechanical work is useful work however, the 15MJ of heat is not a desired output from the process. Whilst there may be a possible use for the heat in another process, if only considering the system of the motor in isolation, the heat must be considered as waste.

[3] Also referred to as the higher heating value (HHV) and lower heating value (LHV) respectively.

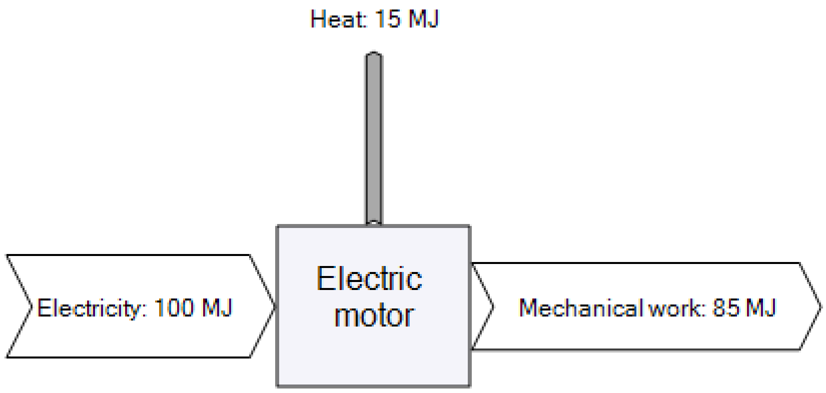

Fig. 2-1: Energy flows into and out of an electric motor.

With reference to equation (2-1) the energy (or first law) efficiency is therefore given by:

$$\eta = \frac{(H_{out})_{useful}}{H_{in}} \tag{2-4}$$

where η is energy efficiency, H enthalpy, and the sub-scripts self-explanatory. Therefore the motor has a first law (or energy) efficiency of 85%.

The first law efficiency is easily understood and calculated at a process level. As the system of investigation becomes more complex, for instance when examining a manufacturing site or subsector, defining the energy input and useful output becomes more complex and thermodynamic measures may not be suitable. This is discussed further in section 2.3.

2.1.3 Reversibility

A reversible process is one where the system and surroundings can be restored exactly to the initial state after the process is completed. An irreversible process is one where this is not the case, the system may be capable of being restored to its initial state but the surroundings cannot (Bejan et al. 1996). A reversible process often represents the ideal case, with irreversibilites representing the real world effects that prevent the process attaining this ideal case. Irreversibilities lead to inefficiencies in a process. Bejan et al. (1996) identify eight effects (although not an exhaustive list) that render a process irreversible:

- Heat transfer through a finite temperature difference.
- Unrestrained expansion of a liquid or gas to a lower pressure.
- Spontaneous chemical reaction.
- Mixing of matter at different compositions or states.
- Friction – both sliding and in the flow of fluids.
- Electric current flow through a resistance.
- Inelastic deformation.

- Magnetisation or polarisation with hysteresis (i.e. the system does not return to its original state after removal of the magnetic force).

The presence of one or more of these effects in a process renders it irreversible. All real processes examined in the context of the current work will contain some irreversibilities. These irreversibilities cannot be eliminated. When examining potential improvements although the conditions that lead to the irreversibilites can be avoided in order to improve efficiency, the irreversibilities themselves cannot be fully avoided.

2.1.4 Exergy

The second law of thermodynamics tells us that real processes occur in the direction of decreasing thermodynamic quality. Forms of energy with high thermodynamic quality are mechanical energy, electrical energy and chemical energy. Given an ideal process, that is the absence of irreversibilites such as friction, all the energy from these high quality sources can be converted to mechanical work. For example if the electric motor in Fig. 2-1 could operate without losses caused by irreversibilities, it could theoretically convert all the electrical energy input into mechanical energy. Energy in the form of heat is subject to different limitations however. Even when a reversible process is employed the proportion of heat energy (*Q*) that can be converted to mechanical work (*W*), in a heat engine[4] is limited by the Carnot efficiency *(η_{Carnot})*. This is defined by the temperature of the source of heat energy *(T_p)* and the temperature of the heat sink *(T_0)* (Cengel and Boles 2002):

$$W = Q \cdot \eta_{Carnot} = Q \cdot \left(1 - \frac{T_0}{T_p}\right) \tag{2-5}$$

All of the heat energy can therefore be extracted as mechanical work if the temperature of the heat sink *(T_0)* is zero. However a temperature of 0K, indicating the absence of all heat energy is not achievable, and holding a heat sink at any temperature below the environmental conditions will itself require energy. The environmental temperature is therefore used as the sink temperature when assessing the maximum work potential available from a given source.

Exergy is a measure of the quantity and quality of energy, it can be defined as: '*the maximum amount of work obtainable from a thermodynamic system when it is brought into equilibrium with its environment via reversible interactions with that environment only*' (Allen 2009). Exergy was a term first coined by Zoran Rant in 1956 (Hammond and Stapleton 2001) and has become the most widely adopted name for a concept that has also gone by the names: availability, available energy, available work, essergy and virtue (Hammond and Stapleton 2001). Exergy analysis has the potential to not only identify where energy is lost in a process (the inefficiencies), as energy analysis does, but also identifies where there is potential to improve on the current process, this is discussed with examples below.

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[4] A device that converts heat energy into mechanical work.

Exergy (*E*) is dependent on both thermodynamic quality (*Θ*) and quantity (*H*), so that (Van Gool 1987):

$$\Delta E = \Theta \cdot \Delta H \qquad (2\text{-}6)$$

Electricity and mechanical work have a thermodynamic quality (*Θ*) of unity. The energy stored in fossil fuels also has a thermodynamic quality of approximately one. It is the treatment of heat energy where values of exergy most diverge from enthalpy. In this case the thermodynamic quality is equal to the Carnot efficiency [see equation (2-5)]. Fig. 2-2 shows how the thermodynamic quality of heat energy varies for a variety of source temperatures, the range of which span most industrial processes. The environment temperature is set at -1°C. There is some divergence of opinion, in the literature, over the choice of environmental temperature used for exergy analysis. Hammond and Stapleton (2001) used a temperature of -1°C in their analysis of the UK, as did Reistad (1975) in his analysis of the USA. This represents the approximate mean outside winter temperature in the UK (Hammond 2004). Rosen and collaborators used 25°C in their analyses of Canada (Rosen 1992) and Turkey (Rosen and Dincer 1997). Wall adopted an environmental temperature of 15°C when analysing Sweden and Japan (Wall 1987, 1990). This is therefore an area of some subjectivity when undertaking exergy analysis, the choice of environmental temperature does have the potential to affect the results of an exergy analysis, especially when there is low temperature heat energy involved.

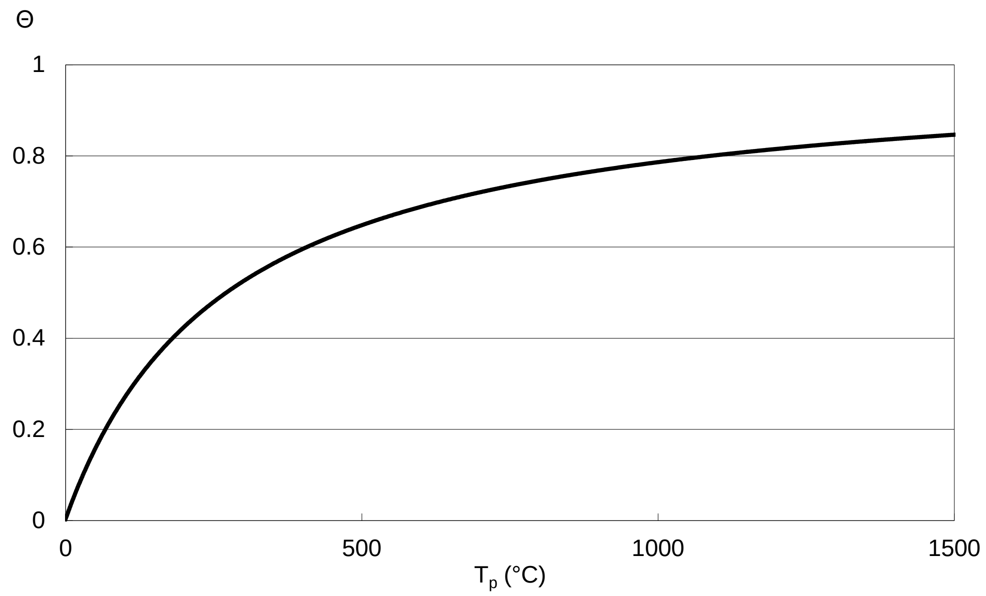

Fig. 2-2: Variation of thermodynamic quality (Θ) of heat energy with source temperature (T_P), sink temperature is set at -1°C [based on a similar diagram by Hammond (2004)].

Exergy efficiency (*ψ*) is defined in a similar way to energy efficiency [see equation (2-4)]:

$$\psi = \frac{(E_{out})_{useful}}{E_{in}} \qquad (2\text{-}7)$$

Therefore when examining processes for which the input and useful output are not in the form of heat the energy and exergy efficiencies are equal (or approximately equal if the input is in the form of fossil fuel). Exergy efficiency is only significantly different to energy efficiency when heat is a component of the input or useful output from the process (as is often the case in industrial processes).

An important difference between energy and exergy is that exergy is not conserved. The second law of thermodynamics tells us the quality of energy will degrade in any real process. Therefore with reference to equation (2-6) it can be seen that exergy must decrease in any real process. The decrease of exergy through irreversibilities is referred to as exergy destruction (Tsatsaronis 2007). Thermodynamic inefficiencies can also arise from exergy losses, where exergy is transferred to the surroundings, via material or energy flows (Tsatsaronis 2007). In the case of losses exergy is not being destroyed, but conserved (as energy is), although the losses are not a useful output from the process. The distinction between an exergy destruction and exergy loss is not always made in studies (Reistad 1975), this is at least partly due to the lack of a formal codifying of exergy analysis [which has occurred for energy analysis (IFIAS 1974)].

Two of the major causes of exergy destruction are combustion and heat transfer. They are involved, in some sense, in almost all energy use in the manufacturing sector, if not directly then in power generation. In combustion approximately a third of exergy in the fuel is destroyed (Dunbar and Lior 1994, Reistad 1975). The majority of this destruction is caused by internal heat transfer accompanying combustion (Dunbar and Lior 1994, Som and Datta 2008), with the actual chemical reaction or fuel oxidisation having an exergy efficiency of 94-97% (Dunbar and Lior 1994). The irreversibilities of internal heat transfer can be reduced by minimising the temperature gradient in combustion, through, for example, preheating of the combustion air (Som and Datta 2008). External heat transfer also causes exergy destruction. When heat is transferred between two mediums it can be seen with reference to Fig. 2-2 that the medium with higher temperature will have a higher thermodynamic quality than the medium at lower temperature. As heat transfer occurs from a higher to lower temperature this indicates a loss of thermodynamic quality with heat transfer. Therefore even with a first law efficiency of 100% (all enthalpy is transferred in the process) an exergy destruction will exist. These exergy destructions can be minimised by reducing the temperature gradient over which heat transfer occurs, this is often not practical however. Based on the above discussion the conversion of exergy stored in a fuel into heat, and the subsequent transfer of this heat, are considerable sources of exergy destruction and irreversibility. Minimising the use of heat transfer and combustion are recommended system design guidelines to maximise exergy efficiency (Bejan et al. 1996), although this can be difficult to achieve in practice.

Exergy analysis can often provide additional insight to a process not given by energy analysis alone. Whereas energy analysis highlights where energy is lost exergy analysis can indicate where there is scope for improvement. A commonly cited example of this is from the work by Reistad (1975), when examining the energetic losses and exergetic destruction[5] arising in a coal-fired steam-electric generating system. The results from this study are shown in Table 2-1. The energy losses refer to the loss of useful energy, as energy is always conserved.

Plant component	**Energy losses (% of plant input)**	**Exergy destruction (% of plant input)**
Steam generator	9	49
Combustion		(29.7)
Heat exchangers		(14.9)
Thermal stack loss		(0.68)
Diffusional stack loss		(3.8)
Turbines	≈0	4
Condenser	47	1.5
Heaters	≈0	1.0
Misc.	3	5.5
Plant total	59	61
Efficiency	$\eta = 100 - 59 = 41$	$\Psi = 100 - 61 = 39$

Table 2-1: Energy losses and exergy destruction in a coal-fired steam-electric generating system. Analysis was undertaken on the basis of GCV. Taken from Reistad (1975).

The overall energy and exergy efficiencies in Table 2-1 appear similar. However the sources of inefficiency identified by the different types of analysis vary significantly. Energy analysis identifies the condenser as the dominating source of inefficiency. In the condenser steam exiting the turbine is condensed to allow it to be pumped. This involves the rejection of enthalpy to cooling water and so it is not surprising that it is a source of significant first law inefficiency. Conversely exergy analysis finds the condenser to cause only a small proportion of the total exergy destruction. This is as the heat being rejected is at a low temperature, close to the environmental temperature (Allen 2009). The processes of combustion, and heat transfer in the heat exchangers associated with the steam generator are the main sources of exergy destruction. This is in agreement with the discussion on the causes of exergy destruction above. Exergy analysis shows that if the exergy destruction in the steam-generator can be reduced energy losses in the condenser will reduce (Reistad 1975). Therefore the exergy destruction in the steam generator imposes a significant limitation on the energy efficiency of the power plant (Reistad 1975). An energy analysis undertaken in isolation would not identify these savings, as the steam generator is responsible for a small proportion of the system's energy losses.

[5] Referred to as exergy loss is the original study, but thought to be exergy destruction as defined in the present work.

Whereas exergy analysis can identify the causes of exergy destruction, other techniques such as thermodynamic optimisation (Bejan et al. 1996) are used to provide practical guidance in reducing any avoidable exergy destructions and losses. Exergy analysis can also be conducted at a top-down level with exergy flows through a nation's economy, or a specific subsector examined. This relies on some broad assumptions and simplifications regarding the use of energy. It can still however offer insights into where the greatest possible improvements in energy efficiency can be made. This technique is applied to UK manufacturing in Chapter 3.

The idea of quality matching arises from exergy considerations. This originated primarily from work by Van Gool and colleagues [for example (Groscurth et al. 1989, Van Gool 1987)]. The principle behind this idea is that, for a system with a number of energy demands and energy supplies, the thermodynamic qualities (Θ) of the supplies and demands should be matched to minimise exergy destruction. It is often observed that using high quality energy carriers, such as electricity and fossil fuels to supply low temperature heat is inefficient when considering exergy (even though the conversion can have a high First Law efficiency). It is therefore preferable to supply demands with a low thermodynamic quality from a source that also has a low thermodynamic quality. The principle example of this in practice is 'heat cascading' where waste heat from one process is used to provide the heat demanded by another process. If there are a suitable number of processes with different temperature demands the heat can be cascaded down a number of quality levels. Combined-heat-and-power (CHP) also uses the idea of using waste heat from a process (in this case electricity generation) to supply demands with low thermodynamic quality. Both the use of CHP and waste heat are discussed further in the current work (see Chapter 3, Chapter 6 and Chapter 7). The technique of quality matching, or heat cascading, requires a high degree of integration within a production site, and possibly also between sites. This is not always possible in practice due to economic and other constraints and so the exergy destruction inherent in using fossil fuels or electricity for heating processes is often unavoidable with the established energy system.

What is described above is a pragmatic approach to exergy, sufficient for the purposes of the analysis here. At a more detailed process level, if information is known about the state of the system under consideration the thermomechanical exergy can be calculated from:

$$E = \left(H - H_0\right) - T_0\left(S - S_0\right) \tag{2-8}$$

where the *0* subscript represents the environmental conditions and *S* entropy[6]. It can be seen from equation (2-8) how exergy incorporates first law (enthalpy) and second law (entropy) concepts in a single measure. This thermomechanical exergy discounts the effect of changes in species concentration. This is not usually significant for analysis at the level of the energy system (Hammond and Winnet 2009). The concept of entropy is difficult to understand for many (the current author included) having no physical basis

[6] The concept of entropy will not be discussed here, a large number of thermodynamics textbooks, for example Cengel and Boles (2002), can be consulted for further information.

to relate to. Exergy, the maximum work available, is a concept more easily grasped by engineers (Dewulf et al. 2008, Hammond and Winnet 2009) and can be used, as discussed, without explicitly considering entropy.

Exergy analysis is a supplementary technique to energy analysis and should not be used in isolation (Hammond and Stapleton 2001). As exergy incorporates both the First and Second laws of thermodynamics it can be elevated above energy analysis, being regarded as the true efficiency by some, this should be guarded against (Hammond and Winnet 2009, Patterson 1993) .There are situations where if only an exergy analysis was undertaken important factors would be overlooked. Bilgen (2000) presents the example of an energy and exergy analysis of a combined heat and power (CHP) plant, consisting of a combined cycle gas turbine and heat recovery steam generator. As the plant's power-to-heat ratio increases the energy efficiency falls significantly, however the exergy efficiency remains almost constant. This is as exergy analysis places much greater value on the electricity being produced, compared to the heat. If only exergy analysis was undertaken the energy loss caused by increasing the power-to-heat ratio would be overlooked.

Exergy analysis assigns a thermodynamic quality to an energy flow according to its capacity to undertake mechanical work under reversible conditions. This is a good indication of quality in a thermodynamic sense, but may not be the only factor relating to the quality, or value, of an energy carrier (Hammond 2004), especially in a complex economic system (Patterson 1993). Work, heat, light, sound and other outputs may be desired from a system. Therefore from a practical, rather than a thermodynamic, perspective the most useful (or valuable) outputs vary (Patterson 1993). There are alternative methods to represent energy quality, these are summarised in a paper by Patterson (1993), which recognised that although accounting for energy quality is a problem that has long been acknowledged, a solution to satisfy all parties has not yet been proposed. Exergy is used here, being a good representation of quality from an engineering perspective and widely adopted in this regard. The limitations of the technique are recognised however.

2.2 ENERGY ANALYSIS

The thermodynamic principles underpinning energy analysis have been understood since the 1800s. However energy analysis did not gain prominence until the period following the first oil price shock in 1973 (Hammond 2000, Slesser 1978). As energy sources suddenly appeared significantly more expensive and insecure than had previously been enjoyed, a method of 'energy accounting' (as the technique was originally known) was of interest. The basic premise of energy analysis is that the conservation of energy principle (the first law of thermodynamics) can be used to trace the flows of energy through an economy, or indeed through a manufacturing site. This allows a gross energy requirement (GER) of a product to be determined. This GER can measure not just the direct energy used in a product's manufacture, but also the indirect energy required to produce the other inputs to the manufacturing process (IFIAS 1974, Slesser 1978). Materials and machinery are examples of other inputs to the manufacturing process. These require indirect energy demands in their production. A system boundary is used to define the scope of an energy analysis, and has an important influence on the results produced. Energy flows are traced back to the system boundary. Therefore to get a full, and true, measure of GER the system boundary needs to be drawn as widely as possible, tracing energy sources back to their extraction from the environment. In practice the national boundary is more often used (Hammond and Winnet 2006) as tracing energy flows from imported materials and energy sources can be difficult. The system boundary of a study can also encompass the use phase of a product's lifecycle (for example the energy used in fuelling a car) and the end of life phase, including disassembly and recycling considerations. Upstream indirect energy use is most important when comparing two products that fulfil the same requirements, but use different feedstocks. For example if comparing a plastic and glass bottle through energy analysis indirect energy use is very important to consider (IFIAS 1974). However, when examining two processes that manufacture the same product from broadly the same feedstocks indirect energy use is less of a concern. As stated in the scope of this work (see Chapter 1) direct energy use is the focus here. It gives sufficient information for the purposes of the study, and allows analysis to be much less data and time intensive.

Energy analysis is traditionally split into statistical energy analysis (SEA), input-output (I-O) analysis and process analysis (PA) (Casler 2004, Hammond and Winnet 2009, Roberts 1978, Slesser 1978). I-O analysis utilises nationally published input-output tables to calculate the GER of a product, it is not a technique that is used in the current work. SEA takes account of direct energy use only and is limited by the availability of statistical data. PA uses more detailed datasets to examine a defined process, manufacturing site or subsector. It can include indirect energy if required, and with the existence of suitable data. The use of SEA or PA is somewhat analogous to the use of top-down and bottom-up studies (as discussed in Chapter 1), and it is these latter headings that will be commonly used in the current work. The use of statistical information reduces the work of the investigator in data collection, however statistical sources also impose limitations on the analysis. The level of industry disaggregation available in datasets may group together subsectors that have significantly different uses of energy. This can make it difficult to draw conclusions from such analysis. The system boundary is determined by the suppliers of the data. This may make data unsuitable, or not ideal for the required application. The current section discusses the important considerations when utilising UK statistics on energy demand for the industrial sector. As discussed by Farla and Blok (2000)[7], data being easily available does not necessarily mean that the problems faced when collecting that data have been avoided but rather that another author has collated the data and made their own assumptions, so '*such problems have become less visible not less significant*'. With any dataset it is important to be aware of the method used in its compilation and any inaccuracies that may arise.

Exergy analysis should not be viewed as an entirely separate technique to energy analysis, but more of a subset of energy analysis. Much of the above discussion on energy analysis is therefore equally valid to exergy analysis. The flows of exergy can be analysed in a similar way as when applying energy analysis, with relevant quality factors applied.

2.2.1 The system boundary – defining energy use and energy-related emissions

When measuring only the direct energy requirement of a site or subsector there are still important decisions to be made over where the system boundary is drawn. This may vary based on the aim of the analysis being undertaken, and also on what data is available. Fig. 2-3 illustrates common energy flows through a site and can be used to help understand the different measures of energy input. The discussion here can be applied to a site or to a subsector, as the data given in statistical sources will be the sum of the site level data.

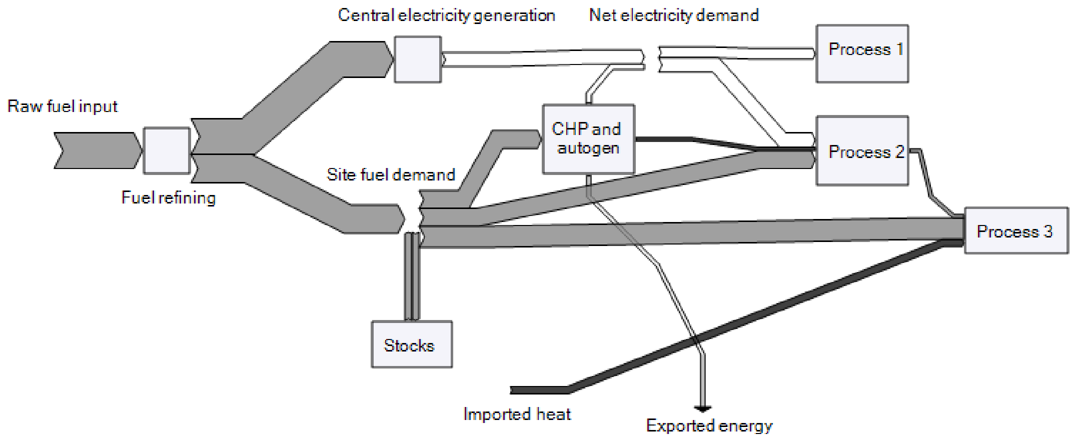

Fig. 2-3: Direct energy flows through the economy to a sample site. Fill colours of the arrows represent the form of energy. Grey represents fuel, white electricity and black heat. Losses not shown, size of flows only for illustration purposes.

[7] The discussion by Farla and Blok (2000) was in reference to economic, rather than energy, statistics. The points made are equally valid here.

At a top-down level energy statistics are relied upon to measure energy demand. In such statistics it is the purchased energy that is usually measured. The Digest of UK Energy Statistics (DUKES) is one of the commonly used sources of such statistics, its system boundary is discussed here. DUKES measures energy demand in terms of 'Final consumption' (final consumption as in DUKES is referred to as final demand here, as energy is never consumed from a thermodynamic perspective). The final energy demand represents the fuel use (after fuel processing) and electricity use of a site. It attempts to provide a basis for a fair comparison of energy use independent of how energy is converted to these final forms upstream. Fuel demand on a final energy demand basis is that delivered to site (with fuel for use in CHP and autogeneration treated differently, as discussed below). The measure of electricity is the sum of that supplied by both large producers and autogenerators (including CHP plants), shown as the 'net electricity demand' in Fig. 2-3. It is therefore independent of the efficiency of electricity production. Fuel used in on-site electricity generation is therefore not included in the final demand fuel totals. Where heat is supplied by combined heat and power plants the fuel required to generate the heat used is given in the measure of final energy demand, combined with other fuel inputs[8]. If heat or electricity are exported to another subsector the fuel use in producing these outputs is not included in the final demand of the subsector. Where heat is imported from another subsector it is listed as a separate fuel. The final energy demand listed by DUKES therefore includes fuels used directly in processes, fuels used to provide heating in the same subsector, electricity both generated within the subsector and imported, and heat imported to the subsector. Fuels may also be used for non-energy purposes in manufacturing (for example as a feedstock in the Chemicals subsector), this demand is not included in the final demand measure. Fuels that are not accounted for are those that are produced by the subsector, and so not purchased, for example wood residues in the pulp and paper subsector. As certain forms of energy (such as solid fuels) can be stored on a manufacturing site the energy purchased may differ from that which is used, if the stocks of energy are not held constant. This is a source of possible inaccuracy when using statistics at a top-down level, although this effect should be minimal.

Energy input into individual processes can be in the form of fuel, electricity, or heat (from a CHP plant, boiler, or an output from another process). Information on individual process energy demand would normally need to be obtained from detailed, bottom-up studies. Fig. 2-3 illustrates how an input to one process can be output from another (for example if employing heat recovery, see the discussion in section 2.1.4). In this case the sum of energy inputs into the individual process would be greater than the energy input when assessed in a more holistic manner.

A limitation of the approach of DUKES, described here, is that importing heat would have a smaller influence on final energy demand than producing heat on-site. To correct for this the imported heat can be converted into a fuel equivalent using the aggregate energy balance of DUKES (DECC 2009b), which lists heat generation under the

[8] DUKES (DECC 2010a) includes methodological details of how fuel input to a CHP plant is split between heat and electricity.

transformation sector, this then allows a fair comparison between heat bought from another sector or produced by the end using sector. Another area of contention related to the definition of final energy demand employed by DUKES is in reference to the iron and steel subsector. The energy used in blast furnaces is not included in the final energy demand of the iron and steel sector in DUKES. Blast furnace energy use is classified within the energy transformation and energy industry use sectors as the blast furnace also produces fuel. However blast furnaces are an integral part of the steel making process, therefore the net energy demand of the blast furnace is included in the iron and steel sector in the analysis of the current work. The procedure for adding blast furnace energy demand to that of iron and steel manufacturing is explained in Appendix 1.

2.2.2 Converting to primary energy and GHG emissions

Primary energy accounts for the energy lost in extracting and converting energy from various naturally occurring forms and delivering it to the site of use. It therefore draws the system boundary as wide as possible upstream of the manufacturing site in terms of tracing the direct energy use back to its extraction from the environment. The most important distinction when using a measure of primary energy as opposed to final energy demand is in the treatment of electricity. Although all fuels will suffer some losses, or require some energy for processing, making the primary energy demand greater than that delivered to the manufacturing site, electricity suffers the highest relative losses in this respect. These losses are also most changeable, dependent on the methods of electricity generation and transmission employed. Generally it can be said that final energy demand is a useful indicator when trying to improve site efficiency, from the perspective of the company. Primary energy is often preferable for policymakers and those considering the global problems of emissions and energy security however (Al-Ghandoor et al. 2010). Similarly the GHG emissions emanating from energy use are often a key concern when considering the impact of energy use on climate change and other environmental concerns.

Converting the final energy demand into primary equivalents and GHG emissions relies on the adoption of conversion factors. The measure of primary energy demand and energy-related GHG emissions can include the effect of all energy used at each stage in delivering the final energy to the end user. Such a measure would include extraction from the earth, refining, transport etc. This method is the most complete approach but can be time and data intensive, and is not required for the current work. There are two situations where the primary energy factor is considered most important here: when considering electricity use, especially when fossil fuels are converted into electricity; and when considering 'Manufactured fuels', where fossil fuels as they would otherwise be delivered to the user undertake further refining, which has an associated energy demand.

Primary energy conversion is based on the factors given for use by companies in reporting for the Climate Change Agreements (DECC 2008). This applies a conversion factor of unity for non-electrical and non-manufactured fuels, for example, a joule of natural gas is equivalent to a joule of coal both from a final and primary energy perspective. This is not strictly true, but is sufficient for the purposes of the current work. The conversion factor for electricity also uses this convention of equality for fuel inputs to power generation in calculating the conversion factor for electricity. Therefore only generation, transmission and distribution losses are accounted for in the primary conversion factor of electricity; this conversion factor and its variation since 1990 is shown in Table 2-2. For manufactured fuel the procedure for calculating the conversion factor is based on information from DUKES, the method is shown in Appendix 1, the value adopted is 1.18.

Year	Final to primary conversion factor
1990	3.20
1991	3.20
1992	3.10
1993	3.00
1994	2.95
1995	2.90
1996	2.88
1997	2.84
1998	2.76
1999	2.68
2000-2010	2.60

Table 2-2: Final to primary energy conversion factors for electricity, UK 1990-2010. Taken from Climate Change Agreement conventions (DECC 2008).

When considering GHGs only the direct emissions are accounted for. In reference to fuels these emissions are those released from the combustion of fuel when it fulfils a final energy demand, not those emissions released in the extraction, transportation, refining etc. For electricity the direct emissions resulting from the combustion of fuels at power stations, including the effect of losses through transmission and distribution of the generated electricity are used to calculate the GHG emission factor. This approach is therefore similar to that for converting to primary energy. Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are included in the emissions totals and converted to carbon dioxide equivalent (CO_{2e}), in terms of warming potential, where possible. The factors used in converting final energy demand to GHGs are taken from the 2010 Guidelines to Defra / DECC's GHG Conversion Factors for Company Reporting (AEA 2010a). The conversion factors for non-electrical fuels are fixed for all years, and are shown in Table 2-3. The GHG emission factor for manufactured fuels is calculated in a similar manner to the primary energy conversion factor, again details are given in Appendix 1.

Fuel	$kg.CO_{2e}/GJ$
Coal	89.5
Manufactured fuel[1]	111.5
Gas oil	76.5
Fuel oil	73.9
Natural gas	51.5
LPG	59.6

Table 2-3: GHG conversion factors for fossil fuels on a final energy use, GCV basis, taken from Defra / DECC's guidelines (AEA 2010a). [[1]Manufactured fuel value is calculated as detailed in Appendix 1.]

For electricity the emission factor varies dependent on the fuel mix and efficiency of generation. This can vary heavily from year to year, based mainly on the relative prices of coal and gas affecting the use of generating capacity. For this reason a rolling year average is used, this is the average value for the previous five years, updated annually. This allows better comparison of the emissions resulting from the use of electricity due to broad changes in system efficiency and overall generation mix. The emission factors used are given in Table 2-4.

Year	$kg.CO_{2e}/GJ$
1990	214.5
1991	210.8
1992	205.2
1993	197.2
1994	191.9
1995	181.2
1996	170.4
1997	159.8
1998	154.0
1999	146.7
2000	143.0
2001	142.0
2002	142.5
2003	143.8
2004	146.8
2005	147.3
2006	148.3
2007	149.6
2008	148.9
2009	146.1
2010	144.6

Table 2-4: GHG conversion factors for electricity on a final energy use basis, taken from DEFRA / DECC's guidelines (AEA 2010a).

The emissions factor for electricity is a good representation when calculating emissions from the electricity used. However, reducing electricity demand will generally result in greater emission savings per unit of electricity saved, than the average emissions per unit of electricity demand. This is as when electricity demand reduces it will be fossil fuel powered generation that is 'turned down' or switched off. Such generation capacity is relatively easily varied to meet load. Conversely nuclear energy cannot easily be varied and is used to meet the 'base load' of electricity, renewables are used to the maximum extent possible, given their availability at a particular time, and the capacity of the grid to support them. Therefore a unit of electricity saved can reduce emissions more than the mean emissions from a unit of electricity use.

Properly accounting for the primary energy equivalent and emissions from electricity use in CHP and autogeneration, by basing this on the actual fuel used rather than the mean for all electricity generation, can be achieved for those sectors for which data is available. This information is only given in terms of six manufacturing sub-sectors however within DUKES (DECC 2010b). Most top-down analysis work undertaken in the current work is at a more disaggregate level. Therefore it is not possible to split electricity use between that from the grid and own generation for much of the work undertaken. Subsequently all electricity use is generally assumed to be supplied by the grid, using the conversion factors above. This means that consequently the primary energy and emissions from those sectors with a significant amount of CHP or autogeneration is likely to be less than calculated. There are generally fewer losses through transmission and distribution when energy is generated locally.

2.2.3 The system boundary – levels of disaggregation and datasets

The current section discusses the level of disaggregation in published statistical sources on energy demand, and related measures, that are utilised in the current work. The datasets discussed include the Digest of United Kingdom Energy Statistics (DUKES), Energy Consumption in the UK (ECUK), the Climate Change Agreements (CCAs) and the EU Emissions Trading System (EU ETS). The variability of energy use within industry makes the level of disaggregation highly important when assessing the worth of a statistical source. A common method of defining subsectors of industry is the Standard Industrial Classification (SIC) system. The SIC system uses a numerical code to define a subsector of industry based on its output. The more digits in the SIC code the more disaggregated into subsectors the data. The area of interest in this work is represented by SIC (2003) 15-37, not including 23 (see Chapter 1). There are various versions of the SIC system. It is updated with time as new products become available, or assume higher importance. Since SIC (1992) was introduced to UK energy statistics in 1995, only minor changes at high levels of disaggregation have taken place to define the SIC (2003) system, which is used in this work (DECC 2012b). SIC (2007), as used in some more recent data releases, has changed the numerical codes used. However, the activities included within the classifications are much the same, and so can be compared with earlier classification systems (DECC 2012b).

The concept of the SIC system appears simple enough. However, where a site produces outputs that belong to more than one SIC grouping the question of how to allocate the energy requirements between the different products is not easily answered (Patterson 1996), with different conventions available (IFIAS 1974). The convention recommended by the International Federation of Institutes for Advanced Studies, when codifying energy analysis (IFIAS 1974), was to assign energy inputs to subsectors based on the physical amount of each output produced. It is doubtful that this is applied consistently however. Inaccuracies are likely to occur, with output and energy demand being wrongly assigned. The SIC system of classification is not ideal for energy analysis applications, being based on grouping industries that produce similar goods, rather than by similar energy usage characteristics. Beyene and Moman (2006) proposed an alternative classification system based on the energy using processes employed in a subsector. This alternative classification was found, in their work, to give more consistent energy use profiles than the SIC system for sites under the same classification. The deficiencies of the SIC system are recognised, however the datasets available often necessitate the use of the SIC system.

The Department of Energy and Climate Change (DECC)[9] publish information on energy use within the industrial sector annually, in the Digest of UK Energy Statistics (DUKES), and Energy Consumption in the UK (ECUK). Information available in DUKES is based on the receipts from sales of fuels and other forms of energy, it is thought to be of good accuracy. The aggregate energy balance for the economy, presented in DUKES (DECC 2009b), splits industry into twelve subsectors at around the two digit SIC level. ECUK provides energy demand data at a much more disaggregate level than DUKES, with information available to the 4 digit SIC code level, giving approximately 240 subsectors of manufacturing. ECUK was originally produced as a report and corresponding data tables in 2002 (DTI 2002). Information in data tables is updated annually and some areas of analysis were extended to give data for periods previous to the original report. ECUK in recent years has also provided information concerning how energy is used in different subsectors of manufacturing (although this is only given at the 2 digit, rather than the 4 digit SIC level). The disaggregated data in ECUK is based on a survey of businesses known as the Purchases Inquiry (PI), which is undertaken as part of the Annual Business Inquiry (ABI, which also provides economic data on industry). The PI surveys approximately 6,000 firms, full methodological details are available from DECC (2010e). Information collected on energy use from the PI is scaled up to match that data presented in DUKES. ECUK is therefore recognised as being less accurate at high levels of disaggregation, being subject to some estimation due to incomplete data. The PI has not been undertaken since 2006 with data for 2007 based on the 2006 survey. Subsequent years data have only been disaggregated to the 2 digit SIC level, representing 22 subsectors of industry. Highly disaggregated energy use data is therefore unfortunately not available for recent years through ECUK.

The information that is available in terms of fuel use tends to be more detailed at higher levels of aggregation. As discussed in section 2.2.2 information on CHP and

[9] Formally DECC's activities concerning energy statistics in relation to manufacturing were covered by the Department for Business Enterprise and Regulatory Reform (BERR) and previous to this the Department of Trade and Industry (DTI).

autogeneration is supplied at relatively aggregate levels only. Similarly the fuel split in the aggregate energy balance of DUKES (DECC 2009b) is at a more detailed level (nine fuels) than in the disaggregated data from ECUK (seven fuels). Information on heat imports (that is heat produced by one subsector, but used by another) are not available in disaggregated ECUK data. Further information on different fuels is also available in DUKES, but again at lower levels of disaggregation only. There have been various methodological changes in DUKES and ECUK data that prevent comparison over all time periods. These are covered in Appendix 2.

Another source of data for energy demand in UK industry is that collected as part of the Climate Change Agreements (CCAs). As part of the CCAs energy demand is reported for each of the covered subsectors every two years, this is available from 2002 through the reports for each target period (AEA 2009b, 2011b, DEFRA 2007b, Future Energy Solutions 2004, 2005b). Further information on the CCAs is included in section 4.2 and Appendix 5, they cover 48 subsectors of manufacturing. As the CCA subsectors have negotiated targets in terms of energy use, emissions, or an efficiency indicator, the existence of a CCA, indicates some uniformity in terms of energy use within the group subject to the agreement. The CCA subsectors therefore have the potential to provide a reasonable level of disaggregation for energy analysis, and are expected to have good accuracy. There are also some significant disadvantages to using this data however. It is generally reported in terms of primary energy demand, without a fuel split. Additionally not all of a subsector is necessarily included in the CCA, especially for less energy intensive subsectors, where only the biggest users of energy may be included. Data is also incomplete for some subsectors for certain years. Information on emissions, output (usually in physical terms) and efficiency indicators can also be provided by the CCAs, but the same limitations apply. The use of CCAs is therefore limited to being a useful comparison for other datasets in the current work.

The EU Emissions Trading System (EU ETS) reports emissions at a site level, the scheme is further explained in Chapter 3, Chapter 4, and Appendix 5. Similarly to the CCAs it generally covers the most energy-intensive industries and sites. The site level data allows a bespoke level of disaggregation to be utilised, which makes the data available in the EU ETS valuable. The EU ETS has been used to build an energy database in this work by converting emissions data to an estimation of energy demand, Chapter 3 and Chapter 6 covers this work.

The energy use provided by datasets can be converted to GHG emissions using appropriate factors as discussed in section 2.2.2. Industrial processes can also emit GHGs as part of the manufacturing process not related to fuel combustion. To get a measure of total emissions a source of process emissions data is required. UK Greenhouse Gas Emissions are reported by DECC (2012k) and are at sufficient levels of disaggregation to combine with energy use and emissions factors information to give an overall level of emissions.

2.3 EFFICIENCY INDICATORS

Defining energy input, and associated measures, has been the focus of discussion in the chapter to this point. Energy input needs to be combined with a measure of useful output to form an efficiency indicator. Useful output can be measured in thermodynamic terms, as discussed in section 2.1.2. A thermodynamic measure of efficiency is useful when considering a single piece of equipment or a well-defined process. A thermodynamic measure can also be used when examining the whole industrial sector, although this requires a considerable level of assumptions and only provides analysis at an indicative level. The useful output from a manufacturing process, site or subsector is ultimately the product, rather than a thermodynamic measure. For this reason useful output is often measured in physical or economic terms. The two most commonly used efficiency indicators are the specific energy consumption (SEC), which is the energy use per unit of physical output (measured in GJ/tonne or similar), and the energy intensity, which is the energy use per unit of economic output (measured in GJ/£ or similar). These are a rearrangement of the traditional efficiency measure of useful output per unit of input, measuring instead the input per unit of useful output. Fig. 2-4 shows how efficiency indicators are often used at different disaggregation levels. The use and limitations of the different indicators are discussed in this section. There are a large number of academic papers on the subject of efficiency indicators in the manufacturing sector (Ang 2006, Bosseboeuf et al. 2005, Cahill and O Gallachoir 2010, Farla et al. 1997, Farla and Blok 2000, Freeman et al. 1997, Nanduri et al. 2002, Patterson 1996, Phylipsen et al. 1997, Ramirez et al. 2006, Tanaka 2008, US DOE 1995, Worrell et al. 1997). A brief discussion of efficiency indicators was also included in a published paper by the current author (Hammond and Norman 2012a). Energy efficiency indicators are important in understanding current energy use, the potential for improving efficiency, and policy. There is, however, no 'best' indicator or widely held conventions, with the choice of efficiency indicator being dependent on data availability and the aim of the study.

Measures of energy efficiency are often meaningless without some basis for comparison (Cullen and Allwood 2010). The efficiency calculated can be compared to the theoretical maximum, best practice, an average value (for a country or subsector), or over a time period. Which basis of comparison is used will, similarly to the efficiency indicator chosen, depend on the system examined, the aim of the study, and data availability.

The useful output from an industrial process could also be the service provided by a product. For example, a steel girder provides a structural service to a building, and the same service could be supplied by a wooden construction. This could potentially use less energy to fulfil the same output (the output being the service of supporting the building), and so be more efficient. However as discussed in Chapter 1 such a material substitution approach is considered outside the scope of the current work and is not discussed further here.

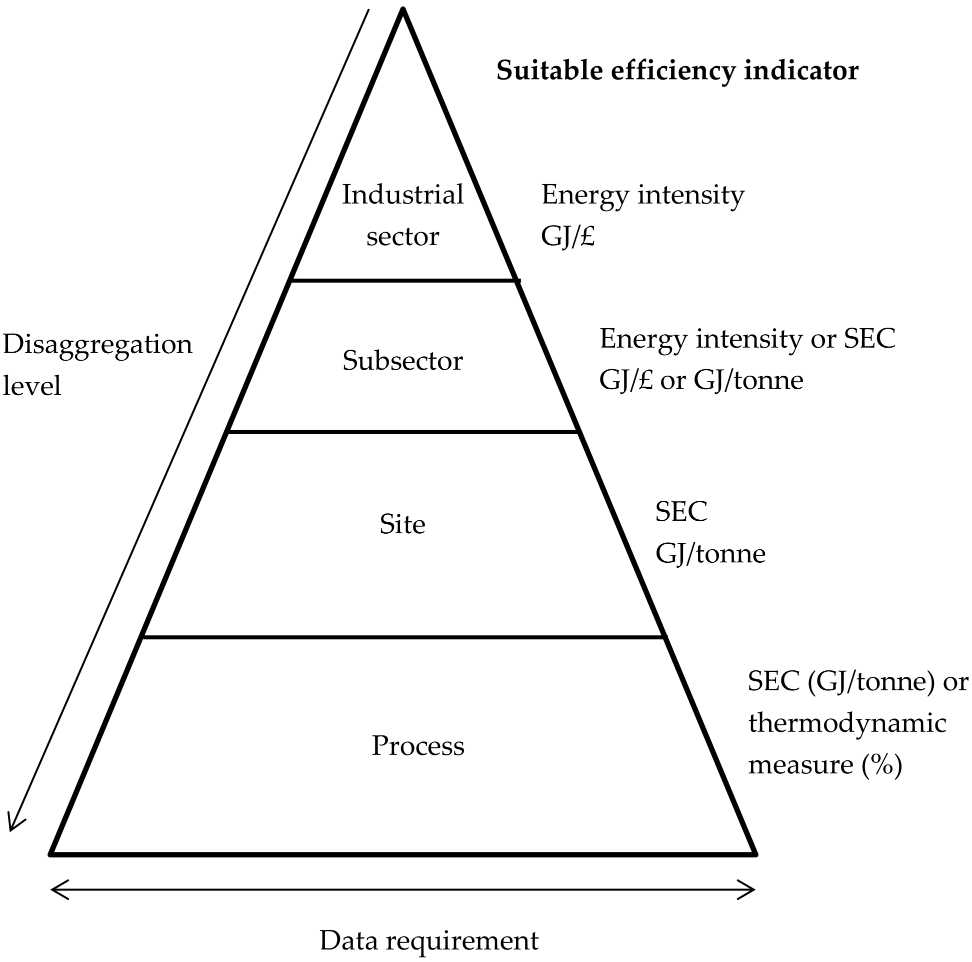

Fig. 2-4: Suitability of efficiency indicators at different levels of aggregation, adapted from McKenna (2009) and Taylor et al. (2010).

2.3.1 Output measures – theoretical and practical considerations

2.3.1.1 Physical output

Manufacturing produces goods, and so these goods are to companies and society a measure of useful output. Measuring these goods in physical terms seems sensible, it is generally accepted as the best measure of useful output from a site, or well-defined subsector of manufacturing (Farla et al. 1997, Farla and Blok 2000, Freeman et al. 1997, IEA 2007, Kim and Worrell 2002, Nanduri et al. 2002, Phylipsen et al. 1997, Ramirez et al. 2006, Ramirez et al. 2005, Worrell et al. 1994, Worrell et al. 1997). Measuring output in physical terms should be objective (Patterson 1996). The measure is therefore suitable for comparison over long time periods (Farla et al. 1997, Patterson 1996) and between nations (Farla et al. 1997, Worrell et al. 1997). Physical output measures are most easily utilised when the output from the subsector under examination is homogeneous. When the outputs of interest are heterogeneous the use of physical output measures is limited. For example a tonne of grain cannot easily by added to a litre of milk to give a meaningful output. Whilst a tonne of cement and a tonne of steel can be summed to produce two tonnes of output mixing outputs like this gives a fairly meaningless measure of aggregate output, it cannot be compared across subsectors, time periods, or countries, unless the product mix is identical (Freeman et al. 1997, Nanduri et al. 2002, Patterson 1996). Even adding together seemingly similar outputs that are of different grades (such as types of steel) could be misleading, dependent on the aim of the study. Techniques have been developed to allow physical output measures to be used at a more aggregate level, overcoming the problem of adding different outputs (Farla et al. 1997, Farla and Blok 2000, Nanduri et al. 2002, Ramirez et al. 2006). However, these can be both time consuming and require large amounts of data (Farla and Blok 2000, Nanduri et al. 2002). The quality of data limits the results more than the choice of methodology used in combining the outputs (Nanduri et al. 2002).

Data on physical output is often best collected on a subsector level with information coming from various trade associations and subsector specific studies The most comprehensive dataset that covers physical output from UK industry is PRODCOM (PROducts of the European COMmunity), this is a survey carried out throughout the EU and supplies information on physical output (and economic output) to a high level of disaggregation (ONS 2012b). In recent years the accessibility of this dataset has improved, but is only available in the current form for 2009-2011. Physical output information is also available within some of the CCAs. As discussed in section 2.2.3 this data only partially covers production and is limited in terms of the time period included.

2.3.1.2 Economic output

The problem of aggregating heterogeneous physical outputs can be overcome by converting these outputs into a common measure of economic value, which can easily be summed. Economic output is of high importance to a company (who are producing goods in order to sell, and make a profit), and also for the nation, when assessing the value produced by the manufacturing sector. Economic measures obviously make international comparisons more difficult however. When used in an efficiency indicator the economic output aims to represent physical output, in a form that is easily aggregated and widely available. There are various ways in which to measure economic output from a company or subsector of manufacturing. Three such measures in common usage are the value of shipments (VS), value of production (VP/ VoP) and value added (VA). Value of shipments is simply the value of sales. Value of production is the value of shipments plus the net change in inventories, and so represents the value of all the goods produced in a defined time period. Value added is the value of shipments minus the cost of materials and services, so presenting the value added to the finished product by the company. From these simple definitions it would appear that value of production is the best measure of actual goods produced. Freeman et al. (1997) show how, disregarding the fluctuations in the price of products with time, the percentage change in value of production will be equal to the percentage change in physical output.

Fluctuations in price can cause inaccuracies in economic indicators. Prices of all goods and commodities fluctuate over time due to inflation, demand and other factors. Consequently a £ of economic output of a product today is unlikely to reflect the same physical output as a £ of economic output of the same product ten years ago. Therefore if useful output is measured in economic terms, and no adjustment is made for these effects, the wrong conclusions can be drawn about the changes in energy efficiency. Price indices are designed to adjust for these fluctuations, by tracking changes in the price of goods produced, and inputs (such as material and fuel), used to calculate economic output measures. The use of price indices allows economic output from different periods to be given in the 'constant prices' of a base year, thereby avoiding the problem of fluctuating prices. 'Constant price' is also often referred to as the 'real price'. Conversely the 'current price' is the price paid at the time of the transaction and is not adjusted for the fluctuations with time.

Price indices can be constructed relatively easily for a well-defined homogeneous product. However, this become more complicated when the output becomes heterogeneous, as it is in many subsectors of industry. Freeman et al. (1997) discuss possible errors when measuring price indices, these are summarised here. Some of these factors can also apply to the measurement of economic output in current terms:

- **Multiple prices:** There may be different definitions in the 'price' of a good, for example output could be measured in gross price or net price (including transportation costs etc). The most appropriate measure of price should be consistently used in any measure of output.
- **Multiple goods:** Most industries produce a wide variety of products, which sell for a wide variety of prices. This product mix will likely vary over time. If the change in product mix is not accounted for, it can cause errors in the measurement of price index.
- **Changes in data underlying industry price deflators:** Methodological changes in measurement, and the way subsectors of industry are classified, can affect the time series of a price index.
- **Quality changes:** If the quality of product increases over time, a good example being the increasing processing power of PCs, there is an issue over whether this change in quality represents a change in the real output or not.
- **Shipments and materials deflators:** Value added includes the cost of other inputs to manufacture in its calculation. These extra costs such as materials and shipping require a separate price index to the output. This adds an additional potential source of error in the output measure.
- **Errors in industry specialisation and coverage:** These are caused when a site produces two or more products, but its entire output is classified by a single SIC code. Output is then overestimated for one of the products and ignored for the other (a similar issue with SIC classification is discussed in section 2.2.3, in relation to energy demand).

As it is difficult to account for fluctuations in the price of products in a perfect manner, and so inaccuracies are likely to exist, it is useful to examine the results from empirical studies of the different measures of economic output and their ability to track physical output. Considerable variability has been observed in this regard, there is no measure that is universally recognised as being superior. Freeman et al. (1997) found that in practice there was little to distinguish the three economic indicators of value of shipments, value of production and value added in their ability to track changes in output volume. When used to represent the useful output in a measure of efficiency the study concluded that all efficiency indicators based on these measures may exaggerate year-to-year changes in efficiency, with value added most likely to exaggerate these changes, and value of production least likely to exaggerate these changes. Ramirez et al. (2005) also found value added more sensitive to changes in the economic environment than value of production (this study was specific to the non-energy-intensive subsector of industry). Conversely Worrell et al. (1997) showed how the economic indicator that best tracks physical production can vary between countries and datasets, as it did in their investigation of the iron and steel sector. Within developed countries value added was found to best track physical production. A study by the US Department of Energy (1995) found that the choice of indicator affected results significantly. Between 1988 and 1991 energy use per unit of economic output was found to increase by 3.4% when using value of shipments. Using value of production there was a 4.5% increase, and using value added there was a 12.7% decrease. The study concluded that when comparing a range of economic indicators (including some not discussed here), value-added was most likely to show outlying results that disagreed significantly with those from other indicators. It seems, from the balance of evidence, that in relation to economic indicators, in most cases value of production provides the best tracking of physical output and value added is most likely to exaggerate changes. It is important to remember that with any economic indicator inaccuracies will occur between it and the physical output.

Value of production can lead to double counting if used to represent the output at an aggregate level by summing the results at more disaggregate levels. This is as outputs from some subsectors can be inputs to other subsectors. Value added subtracts cost of materials from the value of production and so avoids this error. Value-added is therefore suggested by Howarth et al. (1991) and Nanduri (2002) as the preferred measure of economic output. However others suggest double counting in this form is minimal (US DOE 1995). Physical output is subject to these same double counting issues. Similarly to when using physical output measures, adding physically heterogeneous outputs in economic terms can lose meaning if comparing different product mixes. For this reason the technique of decomposition analysis can be used to remove the effect of structural changes on efficiency indicators. Decomposition analysis will itself be limited by the availability of data however, the technique is discussed further in Chapter 5.

2.3.1.2.1 UK data

There are various sources for information on the economic output from UK manufacturing, these listed are all reported in current value terms:

- The Annual Business Inquiry (ABI) (ONS 2009a) gives approximate gross value added (GVA) and a range of other measures of input, output and employment in current value terms. From the ABI value of production (VP) and value of shipments (VS) can be constructed using the data supplied. Similarly to ECUK for energy (see section 2.2.3) the ABI gives data to the 4 digit SIC level of aggregation, it is based on the response to a survey and there are concerns over accuracy, especially at high levels of disaggregation.

- The Office of National Statistics (ONS) Blue Book (ONS 2008) publishes GVA in current value terms. This data is restricted to a fairly high level of aggregation, approximately two-digit SIC codes.
- Input-output tables for the UK (ONS 2010) give GVA for 123 sectors of the economy.

The economic measures that are given in current terms need to be converted to constant prices in order to compare output across time periods. The Production Price Index (PPI) published by the Office of National Statistics (2009b) could be used to convert these prices to constant terms. The price indices are available either at a high aggregation level or at a very disaggregate level (SIC 4 digit and above). The disaggregate data is incomplete for a number of sectors and years. It was therefore not possible to use the PPI, with current value economic measures, to obtain a satisfactory economic output measure in constant prices. If converting a measure of GVA a PPI should also be applied to the measures of input used in calculating the GVA (energy, materials etc.). This is difficult, requiring further information on the inputs and their corresponding PPIs, more inaccuracies can arise due to the extra processing. The author is not aware of any extant measures of GVA or VP in real terms for subsectors of UK manufacturing sector. What is published are an index for GVA in real terms (ONS 2008) and also the Index of Production (IoP) (Office of National Statistics 2012). The IoP measures the volume of production by the manufacturing industry at base year prices. It measures change in gross output (turnover plus net change in stocks and work in progress) (ONS 2009b), which is equivalent to the value of production discussed here. The IoP can be used with a measure of VP obtained from the ABI to give VP in constant prices. A limitation of the IoP method is that the subsector disaggregation is on an economic basis meaning that subsectors that are important from an energy use point of view are aggregated in the measure (for example SIC 27 non-ferrous metals, which includes iron and steel). The highest level of disaggregation possible with the IoP splits manufacturing into seventy two sub-sectors, these are shown in Appendix 3. Value of production in real terms, formed from the IoP and ABI, is the preferred measure of economic output used in the current work.

2.4 ADDITIONAL ASSESSMENT TECHNIQUES

In assessing the improvement available for a given process or subsector the indicators as discussed above can help in an evaluation of technical potential. There are other important aspects beyond this technical potential however, the economics of a change in a process are often critical in its adoption and can be assessed using techniques introduced in the current section. The role of interdisciplinary techniques, which aim to combine two or more different measures in a single metric are discussed. These include attempts to combine thermodynamics with economics and also extending the traditional techniques to include environmental issues, neither approach is favoured based on the discussion here and the techniques are not further developed in the current work. There are additional important aspects regarding the installation of an energy efficient technology beyond technical and economic analysis, these are discussed in Chapter 4, which covers drivers and barriers to realising energy efficient options that are technically and economically viable.

2.4.1 Economic analysis

The techniques presented here allow an assessment of whether an energy efficiency project is economically viable, they also allow the comparison of alternative projects from an economic point of view. An energy efficiency project will generally require an initial investment of capital in order to purchase and install new equipment, and some on-going operation and maintenance costs, the installed equipment should save an amount of energy, which provides a corresponding monetary saving. Therefore capital is spent in order to make savings over the lifetime of the equipment.

An important consideration in an economic assessment is the inclusion of a discount rate. The discount rate allows for the time value of money. It is better to have a pound today than in a year's time as it can be used as capital to invest in projects and gain an income. This should not be confused with the effects of inflation, it is a separate factor. What discount rate is applied to an energy efficiency project is dependent on the investor, what is considered a favourable discount rate by one company may not be by another, a common figure is 5-10%.

There are a number of economic measures that can be useful when assessing an energy efficiency project, these may be assessed on a simple basis (ignoring the effects of discount rate) or discounted, where all cash flows after the first year have a discount rate applied. Commonly used economic decision criteria are:

1. **Payback period:** the amount of time for the investment to be paid off, the net present value (see below) will be zero at this point. This must be less than the lifetime of the project to be profitable.

2. **Accounting rate of return:** the average annual savings as a percentage of initial investment, this is on simple terms (not applying a discount rate).

3. **The net present value (NPV):** the sum of all discounted cash flows at a given point in the project's lifetime. At a given point if the NPV is positive the investment is showing a profit.

4. **Discounted cash flow (DCF) rate of return (or yield):** the discount rate that must be applied for the project to have a NPV of zero over its lifetime. A higher yield indicates more return on the initial investment
5. **Benefit/ cost ratio:** the project's ratio of benefits (savings) to costs.

To calculate the present value (PV) of a payment the final value (FV) must be multiplied by a present value factor (PVF).

$$PV = FV \times PVF \tag{2-9}$$

Where the present value factor can be calculated by:

$$PVF = \frac{1}{(1+r)^n} \tag{2-10}$$

Where *r* is the discount rate and *n* the number of years.

Therefore with a discount rate of 5%, £1 received in five years' time would be worth 78p today. When applying a discount rate to any of the above decision criteria the PVF can be applied to each cash flow to give future cash flows in present value. When the project consists of an initial investment (I) and an uniform annual revenue (R) this process can be simplified by the use of the following:

$$\begin{aligned} NPV &= -I + R\sum_{0}^{N}(1+r)^{-n} \\ &= -I + R\left[\frac{1-(1+r)^{-N}}{r}\right] \end{aligned} \tag{2-11}$$

As well as using equation (2-11) to calculate NPV it can be used to find payback time, by setting NPV to zero and varying the value of *N* for a given discount rate (*r*). To calculate the DCF rate of return, NPV is set to zero, *N* is set to the lifetime of the project and equation (2-11) is solved for *r*.

Any or all of the above criteria may be used by an investor to assess a project. An investor will have a limited amount of capital and so projects which perform well according to the chosen economic criteria will likely receive funding before others. There are other considerations to a project beyond its economic viability. Barriers to energy efficiency projects are discussed in Chapter 4.

There are, of course, uncertainties surrounding the costs and benefits of projects, especially into the future. Specifically related to energy projects the future price of energy is subject to a great degree of uncertainty and this can considerably affect the outcome of an economic analysis. Methods to account for this risk can be applied.

1. **Higher discount rates:** applying a higher than normal discount rate allows for future risks. This assumes risks increase with time, which may not always be the case.
2. **Risk analysis:** probabilities are assigned to key variables and a probability distribution of the decision criteria can be obtained.

3. **Sensitivity analysis:** variables are changed and the effect on the decision criteria is observed. For some variables, it may be found that, small fluctuations could cause large changes in the decision criteria.

Uncertainties can similarly exist over the technical performance of an efficiency measure, especially if the technology is novel. A sensitivity analysis can also be used to examine the likely effects of uncertainty on future levels of energy and emissions when applying a new technology.

2.4.2 Interdisciplinary techniques

The subject of energy use and its environmental effects encompasses a large number of fields of study, engineering, economic, environmental and social issues can all be important considerations. Whilst techniques exist within each of these fields for analysis, for example the engineering and economics approaches discussed above, there have been attempts to combine multiple areas of study into a single measure of analysis. These techniques are referred to as interdisciplinary techniques. The concept of sustainability is itself multidisciplinary, attempting to balance economic and social development with environmental protection (Hammond and Winnet 2009). It is therefore attractive to combine different disciplines to cover different aspects of sustainability in a single measure. However this can be dangerous as important effects appreciated from investigating each area individually can be overlooked. Two areas discussed here, thought to be most relevant to the current work are the extension of economics to allow for environmental and ecological effects and the use of energy and exergy concepts to represent value beyond the thermodynamic sphere.

2.4.2.1 Extending economics

Neoclassical economics involves the type of analysis discussed above in section 2.4.1. A key concept of this field is that the price of a product or service is determined by the value placed on it by society. Therefore in a complete and perfect market economics is normative, that is that it determines the best course of action from a series of choices (Hammond and Winnet 2006). In practice however markets are rarely complete or perfect. Social costs, including environmental effects do not have prices and so cannot be accounted for. Uncertainties about the future, especially technological change may also limit the effectiveness of the neoclassical model. If these uncertainties are not reflected in prices it may lead to suboptimal decisions.

To overcome the deficiency of neoclassical economics in accounting for environmental effects the field of environmental economics has been developed. Environmental economics attempts to price emissions, pollution and other environmental effects so they can be incorporated into the framework of economics. There are a number of common criticisms of this approach. Firstly it is not clear how to assign a price to an environmental effect, and a number of methods that have been proposed (but shall not be discussed here) are open to criticism (Hammond and Winnet 2006). How the price is assigned can have a significant effect on results (Hammond and Winnet 2009). Secondly, and perhaps more importantly including environmental effects in an economic measure can make these effects easier to ignore (Hammond and Winnet 2006). The decision maker can be presented with a single metric that supposedly takes account of the environmental effects of the different options for a project. An understanding of the environmental effects can be lost, and they can be ignored once given a price. Environmental economics can offer a valuable insight, however like any analysis technique there are limitations that should be recognised and it is dangerous to rely on a single measure to encompass a range of effects.

2.4.2.2 Extending thermodynamics

In the early 1970s an energy theory of value was proposed that based economic value on the amount of embodied energy of a product. It was thought this could help represent the issue of resource depletion and environmental damage. As a product moves through the economy, gaining more economic value, energy is required at each step (Sollner 1997). However energy cannot encapsulate the full range of factors, economic and social, that determine the value of a product (Sollner 1997). An energy theory of value is therefore open to criticism. Second law concepts have been similarly extended. The measure of energy dissipation offered by second law concepts, is thought by some, to mirror the path of natural resources and energy through the economy. The use of exergy to represent concepts beyond thermodynamics has been adopted by practitioners from a range of fields, including both economics and ecology. Exergy has been used in ecological economics as a measure of the use of natural resources and the environmental effects of an economic system. High exergy sources are withdrawn from the ecosystem (in the form of, for instance, fossil fuels) and low exergy waste is rejected back to the ecosystem from the economic system (Hammond and Winnet 2009). This has led to the development of exergy accounting (also called exergy costing or exergoeconomics) which performs analysis on an energy system, assigning economic value to inputs (both energy and material), waste streams and other outputs based on their exergy content. This therefore highlights the cost of waste and irreversibilities to a system, it can make costs, both for equipment, losses and fuel savings more visible (Hammond and Winnet 2009). Exergoeconomics can therefore help optimise a system in terms of the financial costs. Similarly to the energy theory of value this approach has been open to criticism. Whilst thermoeconomics (a term encapsulating the combination of thermodynamics with economics), especially exergoeconomics can be used to gain valuable insights (Hammond and Winnet 2009) any link between exergy and concepts outside of the thermodynamic sphere, be they related to economics, resource depletion or ecology are analogical rather than literal. These techniques should be used with caution. As discussed in section 2.1.4 exergy is a measure of the maximum amount of work theoretically obtainable from a system, but nothing more. There is no direct link between thermodynamics and economic systems (Sollner 1997). Proponents of exergoeconomics do agree the traditional monetary price tag should not be dismissed, but used in addition to that through exergoeconomics (Dewulf et al. 2008). Hammond and Winnet (2006) argue the combination of exergy and economics in exergoeconomics is like mixing *'chalk and cheese'*, due to the fundamental differences between economics (being normative) and thermodynamics being solely descriptive, imposing no value judgements.

An example of the extension of thermodynamic techniques can be found in the use of exergy analysis in macro-scale, top-down studies. Exergy analysis of a complex economic system was originally adopted by Reistad (1975) and quantified the exergy flow of energy carriers. This methodology has been extended, firstly by Wall (1987) in assigning exergy values to flows of materials and also waste and emissions. Sciubba (2005) further extended this, by assigning exergy values to labour and capital. These techniques should be used with caution, especially in the case of Sciubba's method, often known as extended-exergy-accounting (EEA) as assigning exergy values to labour and capital is only ever an analogy. Assigning exergy values to materials and wastes can be done, as these substances are not in equilibrium to their environment and therefore have an exergy value. However this exergy value, the capacity to undertake work does not represent their worth to society as materials, or the environmental damage inflicted by wastes. Similarly to exergoeconomics, such an approach can offer useful insights, but is also in danger of hiding factors that could perhaps be better understood by examining the different areas of sustainability through separate techniques.

2.5 SUMMARY

A key point from the discussion of analysis techniques presented here is that no single technique can encompass all the important factors when assessing an energy efficiency project. The current work focuses on engineering based measures, but this does not mean other techniques are unimportant or do not require consideration. A 'toolbox' of assessment techniques should be utilised to provide the best assessment of a technology or improvement potential. With all analysis techniques a qualitative understanding of the situation is also valuable, for deciding on the most appropriate techniques to employ, and in understanding the results of an analysis, placing them into context.

When an analysis technique is used the choice of method and parameters, such as the system boundary, are often a compromise between completeness of analysis and completing the study in a timely manner, avoiding over-complications. In this work direct energy use is the principal concern, indirect energy use can be important in certain situations, but is much more time consuming to fully measure. The statistical datasets available regarding direct energy use within the UK industrial sector have been discussed in this chapter.

Energy efficiency in a thermodynamic sense is the most familiar efficiency measure to an engineer and it could be argued to be the most objective measure, with clearly defined conventions. Exergy analysis can act as a supplement to energy analysis, providing additional insights and signposts for improvement potential. Thermodynamic measures are often best suited to the process level. Measuring output in terms of products becomes more meaningful above the process levels. How output is measured is dependent on the aim of the study and data availability. In general physical measures of output are preferred but can be difficult to aggregate and are not as widely available as economic measures. Value of production is the preferred measure of economic output, when used in an efficiency indicator. The availability of data heavily influences what indicators can be used for a specific level of disaggregation. When comparing energy efficiency indicators across time periods, sites, regions etc., the indicators will likely include other effects, such as differences in product mix. It is difficult to avoid these inaccuracies, but they should be recognised as a limitation of such analysis.

An understanding of the different economic assessment methods is useful when examining energy efficiency improvement potential, even if economic techniques are not directly used in the assessment. Similarly interdisciplinary techniques have been discussed in the chapter. These are not utilised further in the current work, but offer insights when considering a holistic approach to assessing energy efficiency technologies.

CHAPTER 3

THE TOP DOWN PERSPECTIVE

Examining energy use throughout UK industry primarily relies on national level statistics. Whilst this approach has limitations in terms of the conclusions that can be drawn from a broad study, it is the first step in understanding the sector, and putting more detailed work into context. In an effort to improve the data available for top-down studies a database was built from site level emissions data available through the EU ETS. This allowed higher levels of detail and disaggregation compared to publically available datasets. This database was compared to those that are freely available in terms of the energy demand of different subsectors and the end use of energy. This new database was built for a limited time period (2000-2003), expected changes since this period in terms of output levels and efficiency were examined. A thermodynamic analysis, examining the flows of energy and exergy through the manufacturing sector, using the information available within the constructed database, and a comparison to other studies of this nature, was undertaken. Although many improvement opportunities in the industrial sector are process specific, there are a number that can be considered 'cross-cutting'. These opportunities are applicable to multiple subsectors of manufacturing. Improvements to motor systems, steam systems and the increased use of combined heat and power (CHP) are three such opportunities. The potential for the application of these technologies throughout the manufacturing sector was examined and is included in the current chapter.

3.1 BUILDING A DATABASE

As discussed in previous chapters, a significant limitation on an analysis of the industrial sector in the UK is imposed by the lack of detailed and accurate data, relating to energy use at a disaggregated subsector level. To overcome this challenge, alternative sources to the published statistics on energy use were sought. The National Allocation Plan (NAP) of the European Union Emissions Trading System (EU ETS) provides carbon dioxide emissions data on a site-by-site basis for those sites included in the EU ETS (see Appendix 5 for details on the EU ETS). These sites are the greatest emitters of carbon dioxide in the industrial sector. In broad terms a site is included in the scheme if it has a combustion plant of over $20MW_{th}$ (or multiple smaller plants that sum to this total), or is within a subsector that is carbon intensive, and its output is over a certain threshold. Full details of inclusion are published by DEFRA (2007d). Utilising the emissions data in the NAP, with knowledge of the activities taking place at the sites, allowed energy use to be estimated at each of the sites, as detailed below. The work in constructing this database was originally undertaken on behalf of the Energy Technologies Institute (ETI). The work was subsequently published in a report (McKenna et al. 2009), as well as a peer reviewed academic journal (McKenna and Norman 2010). The current author was a co-author of both of these publications, the journal paper is reproduced in Appendix 6. The main author for the initial work also published it as part of his PhD Thesis (McKenna 2009), where the fullest account of the original methodology can be obtained, this shall not be repeated in its entirety here, the main points are included. Some refinements to the original methodology were adopted for the current work and are detailed below.

3.1.1 Methodology

Each site in the NAP (there were 521 sites in total) was classified within one of forty-eight subsectors (results are shown in a more aggregated manner throughout this chapter for ease of interpretation, the full split of subsectors is shown in Appendix 4). These subsectors were chosen so that each represented a reasonably well-defined process route and use of energy. This both allowed the database to be constructed, as detailed here, and facilitated further energy analysis. There were some subsectors that necessitated a more generic approach to the site operations. These were relatively small users of energy, for whom it was more difficult, and less important, to examine the site energy use in detail. These sites were generally treated as users of steam systems, they are discussed within section 3.2 below. Each subsector defined in the database could be represented by a SIC code. However these SIC codes would be at various levels of disaggregation, between two and four digit.

For each subsector the load factor, process emissions and fuel split was estimated, based on published data [see McKenna (2009) for full details]. With the use of fuel emissions factors this allowed energy demand at each of the sites to be estimated. In essence this reverse engineered the manner in which the emissions were reported, as sites usually convert their fuel use into emissions for reporting purposes. The energy use data obtained in this manner was supplemented with information on output and specific energy consumption (SEC) for important sites either not included in the NAP, or poorly represented by emission levels.

In the original work (McKenna and Norman 2010) it was assumed that all fuel use went to heating processes and electricity use was for non-heating uses [with the exception of subsectors for which it was known a large amount of electricity was used for heating processes, namely Aluminium production and the Electrical Arc Furnaces (EAF) route of steel production]. Only heating processes were of interest in this original work and so other energy use was ignored. This was updated for the current work, both as non-heating processes were important in an overall assessment of energy use, and to improve the estimate of electricity that goes to heating uses. Information from ECUK (DECC 2009d, 2010d) was used to estimate the proportion of electricity that was utilised for heating processes in each of the subsectors. All fuel demand was assumed to all be used in heating processes (based on information from ECUK). The remainder of the electrical demand was assumed to be used in motor systems (including compressed air and refrigeration). This methodology did not include electricity usage for lighting and other uses. However, given the small proportion these end uses account for in the industrial sector, and as the NAP only includes the greatest emitters of carbon dioxide (meaning that these uses take on even smaller importance), this seems a valid assumption. Exceptions to the described methodology occurred when it was felt the information provided in ECUK (DECC 2009d, 2010d), which was at a two digit SIC level of disaggregation, did not accurately represent the electricity use of the subsector as in the database. Details of the electricity use to heating processes for each subsector are given in Appendix 4, with notes explaining any difference from that value given in ECUK. Heating demand was estimated based on the expected efficiency of converting the fuel source into heat (McKenna 2009). The heat demand was then split between five temperature bands, again with knowledge of the energy using process within each subsector. The temperature bands are detailed in section 3.1.2 below. It was assumed that below 500°C energy was supplied by steam systems. The waste heat available for recovery was also estimated for each subsector. This information was used in Chapter 6 to analyse the heat recovery potential of UK industry.

Emissions from CHP plants were reported separately in the NAP and so could be analysed accordingly. Details on the CHP plants including heat-to-power ratio, load factor, efficiency, and fuel split were estimated for each subsector in a similar manner to non-CHP emissions and so the fuel demand of CHP plants could be estimated, as could the heat and electricity output. The heat from CHP plants was assumed to be used in steam systems within the parent sector. A proportion of electricity produced by CHP plants was assumed to be utilised for heating and by motor systems in order to preserve the same split of end uses of energy as in the CHP parent subsector. Excess electricity was assumed to be exported to other sites or the national grid, and so used to offset electricity demand of the subsector or manufacturing sector as a whole.

The constructed database offers significant advantages over the publically available datasets discussed in Chapter 2. The disaggregation into subsectors was chosen with a view to energy analysis. The database therefore allows analysis to be undertaken at a higher level of disaggregation than would be available through DUKES, whilst not having the same concerns over accuracy associated with data in ECUK. Data was available at the site level, this allowed analysis of options based on the magnitude of site level demands to be undertaken (for example see section 3.5.3 and Chapter 6). This was not available from another dataset.

There were limitations to the database constructed. Not all of the industrial sector was covered, approximately 60% of industry, and 90% of energy-intensive industry in terms of final energy demand was represented. Section 3.2 includes a full comparison with published datasets. The NAP used was for Phase II of the EU ETS and was based on the average emissions from 2000 to 2003, minus the lowest year for the majority of sites (DEFRA 2007c). This data therefore represents the state of the industrial sector at the beginning of the last decade rather than a specific year. There has been a significant fall in energy use since this period, primarily caused by the recession in the UK of 2008/09, and subsequent reduction in industrial output, including the closure of some large sites. Changes between the time period of the database and the time of writing are discussed in section 3.3. The methodology utilised subsector average parameters to calculate site level data. The subsectors were chosen to allow this methodology to be used, and so to have homogeneity in terms of energy use throughout the sites under each subsector classification. However, there are still assumptions and inaccuracies in such an approach. Even where the subsectors produce very homogeneous outputs, and the energy demand data for the subsector as a whole is found to correspond well with other datasets (see section 3.2), variation would still be expected in fuel split and other parameters at the site level. These variations and hence inaccuracies are greater in those subsectors that have a varied product output and energy use. A broad classification of subsectors by their output (homogeneous or heterogeneous) and a qualitative assessment of the accuracy of their representation in the database is provided in Table 3-1. The reasons for concerns regarding accuracy are best explained on a subsector by subsector basis, and the reader is referred to the most complete discussion of the original work for full details (McKenna 2009).

	Qualitative measure of accuracy		
Sector classification	**Fair**	**Good**	**Excellent**
Homogeneous	Other sectors[10]	Ceramics (bricks) Pulp and paper	Aluminium Cement CHP Glass Lime
Heterogeneous		Chemicals Food and drink	Iron and steel

Table 3-1: Classification of sectors as homogeneous or heterogeneous and qualitative indication of the accuracy of representation (McKenna and Norman 2010).

3.1.2 Energy demand results

Fig. 3-1 shows final and primary energy demand by subsector and use of energy. In common with DUKES, as detailed in Chapter 2, final energy demand includes fuels and electricity used directly by the subsectors. In the case of CHP this includes the fuel used to supply the heat portion of the output and the net electricity produced (rather than the fuel input to generate this electricity) that is used by the subsector. Allocation of fuel use in CHP facilities between heat and electricity outputs was based on DUKES (DECC 2012b). Primary energy includes the fuels used directly by the subsector (with a primary conversion factor of unity) and the fuels used in producing the electricity demand, both offsite by large electricity producers (in which case a primary energy conversion factor of 2.6 is used) and by CHP plants (in which case the fuel used to generate the electricity is included).Iron and steel accounts for 31% of total energy demand on a final energy basis, with Chemicals accounting for 24%, Food and drink and Pulp and Paper each account for 11% of final energy demand. The difference between primary and final energy demand is relatively greatest where a large proportion of electricity is used, for example in the Aluminium subsector. CHP systems have significant use in the Chemicals, Food and drink and Pulp and paper subsectors.

[10] Strictly speaking other sectors are heterogeneous, but they have been lumped together and treated as boilers and steam systems in this case, and hence are considered to be homogeneous. These sectors count for a very small proportion of the overall energy demand, as shown in Fig. 3-1.

Fig. 3-2 shows final energy heating demand split by subsector and temperature band. Iron and steel dominates demand in the highest temperature band. A total of 560PJ/yr of heat energy is demanded by the 521 sites in this database. A significant proportion of this heat is provided by CHP in the two temperature bands below 500°C, specifically within the three subsectors highlighted as large users of CHP.

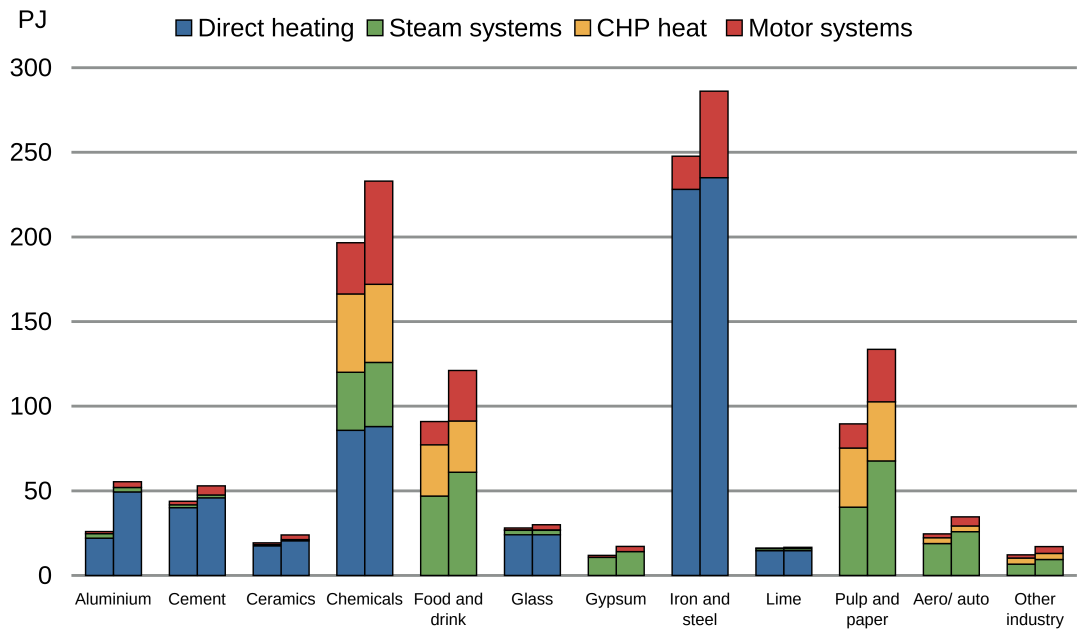

Fig. 3-1: Annual final energy demand and primary energy demand by subsector and use of energy based on data in the NAP.

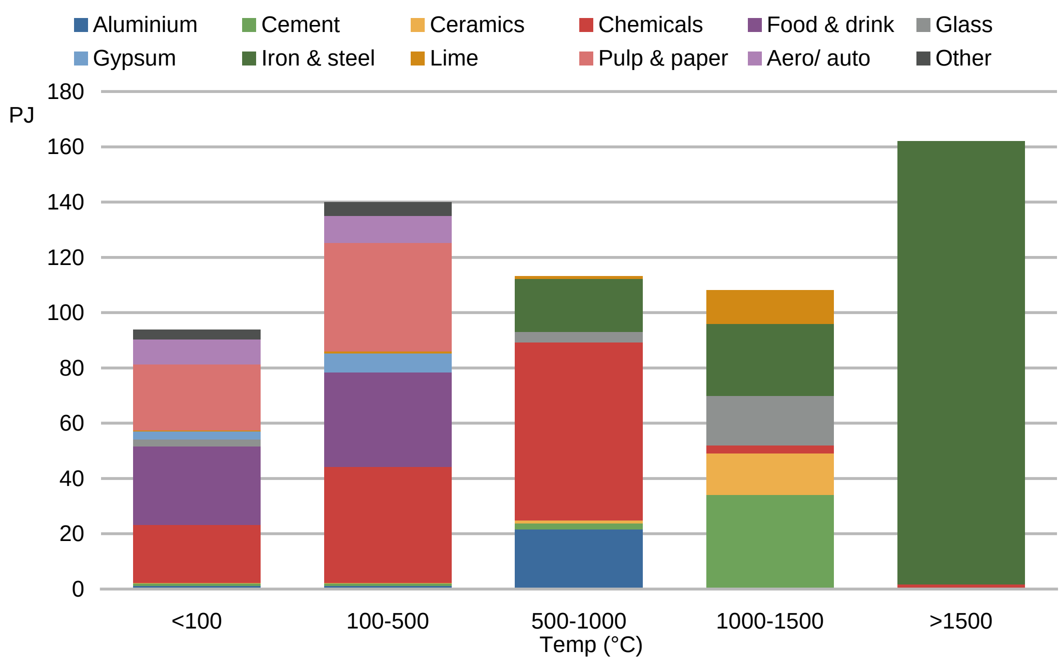

Fig. 3-2: Annual heat demand in final energy terms by subsector and temperature demand.

3.2 DATASET COMPARISON

Table 3-2 summarises the results, showing the total energy demand of different subsectors using the constructed database (NAP), in comparison to datasets from ECUK (DECC 2009c) and the First Target Period (TP1) of the Climate Change Agreements (CCAs). The time periods of the data have been matched as far as possible.

Subsector	Final energy use (PJ)			Primary energy use (PJ)		
	NAP	ECUK	Share in NAP (%)	NAP	CCA TP1 2002	Share in NAP (%)
Aluminium	26	30	86	55	62	89
Cement	44	39	113	53	58	91
Ceramics	19	23	82	24	49	49
Chemicals	197	263	75	233	288	81
Food and drink	91	161	57	121	205	59
Glass	28	27	106	30	42	71
Gypsum	12	0	4473	17	8	226
Iron and steel	248	234	106	286	281	102
Lime	16	2[a]	719	17	9[b]	180
Pulp and paper	90	55	162	134	103	130
Aero/auto	25	66	37	35	19	178
Other industry	12	430	3	17	120	14
Total industry	807	1331	61	1021	1245	82

Table 3-2: Comparison of annual energy demand in NAP data, compared to ECUK (based on 2000-2003 minus lowest year data) and CCA TP1 (2002). [a]11PJ from 1996-1999, [b] excludes in house production.

The majority of subsectors show good agreement between the data derived from the NAP and other datasets. The energy demand in the NAP database depend on both the accuracy with which the site level emissions data has been converted into energy, and the coverage of the sites in the NAP. The accuracy of the other datasets is also important when comparing results. ECUK should cover all energy use in a subsector, although as discussed in Chapter 2, there are concerns over the accuracy of the dataset at high levels of disaggregation. The CCAs (similarly to the EU ETS) only cover those sites that are significant users of energy. Generally, the limits for inclusion are lower for the CCAs than the EU ETS, i.e. a site in the EU ETS will almost certainly be included in a CCA, however there are many sites involved in CCAs, but not the EU ETS. It should also be noted that the CCA data is for a single year (2002) whilst the NAP data covers 2000-2003, minus the lowest year. Comparing the total industry energy use between datasets the sites in the NAP cover 61% of total energy use (as reported by ECUK) and 82% of those sites included in the CCAs. Good agreement is found between datasets in the Aluminium, Cement, Chemicals, Glass, and Iron and Steel subsectors. The Food and drink subsector is not covered as fully by the NAP, this would be expected as the subsector includes many smaller sites (see Chapter 7 for further discussion of the Food and drink subsector). Parts of the Food and drink sector are also treated fairly generically in determining energy use from emissions data, by assuming energy use for heating is all for steam systems (McKenna and Norman 2010). This same assumption is also true of parts of the Chemicals, Pulp and Paper, Aero/ auto and Other subsectors. This explains some of the discrepancies between datasets, although this approach is still felt to give a fair representation of energy use. The Ceramics subsector is an area where there were doubts regarding the accuracy of the NAP database. This was due to the difficulty in classifying different sites to different subsectors. Within Ceramics there can be considerable variations in terms of energy use (McKenna and Norman 2010). The Gypsum subsector appears overrepresented in the NAP. There are concerns about accuracy in the ECUK data, with uncertainties regarding the classification of Gypsum manufacturers under the SIC system. It is thought that sites classified as Gypsum producers in the NAP may be classified differently in other sources, hence the discrepancy with the CCAs. The Lime subsector also appears over represented in the NAP. It is thought to be poorly represented in ECUK, having shown much higher energy demand in recent time periods. The CCA does not cover all production, significantly it does not cover in-house production for British Sugar and Corus (DEFRA 2001). The Lime sector as represented in the NAP is therefore thought to be a more accurate model. This comparison highlights some of the shortcomings of statistical data and the classification of outputs using the SIC system, as were discussed in Chapter 2.

3.2.1 End use of energy

Fig. 3-3 shows final use of energy by subsector according to ECUK (DECC 2010d), with additional calculations by the author[11]. A low level of disaggregation in this data prevents similar subsector groupings to those presented for the NAP data. Fig. 3-4 shows the final use of energy for the entire manufacturing sector and compares measures of final energy demand, primary energy demand and energy-related GHG emissions, also based on the ECUK dataset. Original data was in terms of final energy demand, conversion into primary energy and GHG emissions was based on the conversion factors discussed in Chapter 2. Although the information presented in Fig. 3-3 and Fig. 3-4 is for a different time period than the NAP data (this information was not available over the same period covered by the NAP data) a broad comparison of energy use should still be possible,. Similar information for the NAP is shown above in Fig. 3-1, and below in Fig. 3-9.

[11] The addition of blast furnace energy use to the Basic metals subsector (see Appendix 1).

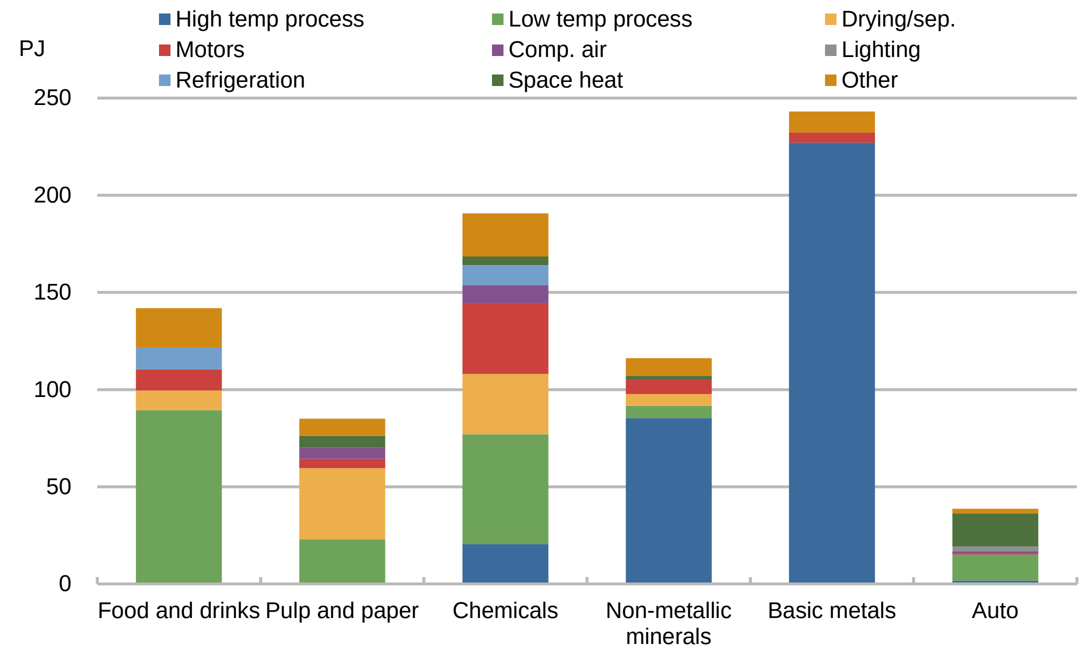

Fig. 3-3: Energy use by subsector, 2008 (DECC 2010d). Data have been modified from those published with blast furnace energy use also added (see Appendix 1).

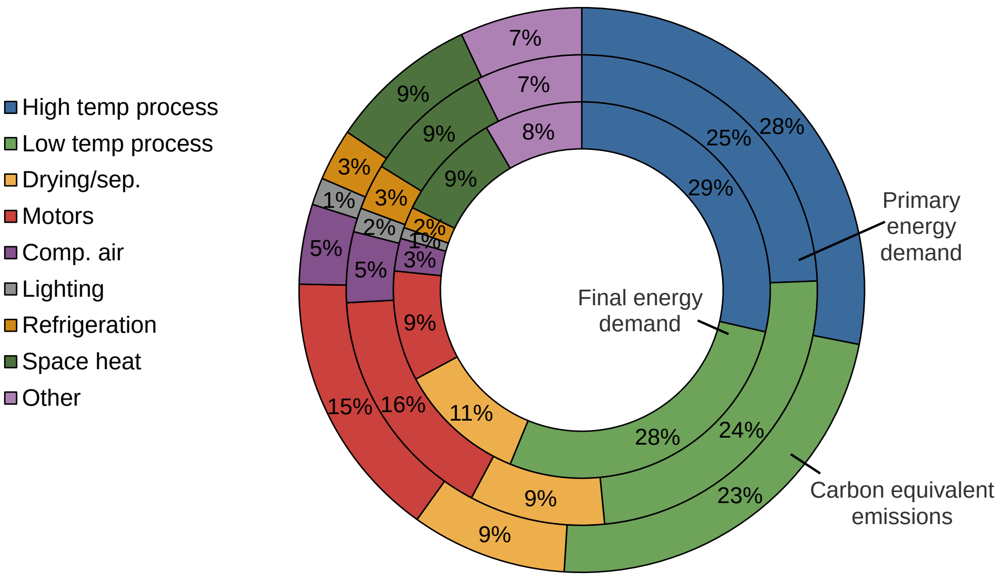

Fig. 3-4: Final uses of energy in manufacturing, 2008 (DECC 2010d).

Overall heating use accounts for 89% of final energy demand according to the NAP database, this compares to 77% in ECUK. A higher proportion of demand going to heating processes would be expected at the sites in the NAP as they represent energy-intensive users of energy with large heating installations. As shown in Chapter 4 the energy-intensive subsector does tend to use a higher proportion of energy in heating processes in comparison to the non-energy-intensive subsectors. 47% of electricity demand goes to heating as an end use according to the NAP data, ECUK estimates this as 46%.

Comparing Fig. 3-3 and Fig. 3-2 there is generally good agreement between the different datasets, in relation to the temperature of heat demand. ECUK is more limited in this regard, as the definition of low and high temperature processes is not as detailed or well-defined as the NAP source. The compilers of the data are themselves somewhat unsure of the exact definition of each end-use. It is thought low temperature processes include those up to at least 300°C (Knight 2008). ECUK does not offer any information on the amount of heating supplied by steam systems, the IEA (2007) estimates that steam systems represent 35% of UK manufacturing energy use. According to the NAP database it is also 35% (this includes CHP heat output). In assigning all heat demand less than 500°C to steam systems, and all heat demand over 500°C to direct heating, steam system use will be overestimated for some subsectors (e.g. Food and drink) and underestimated in other subsectors (e.g. Iron and steel). Due to their energy-intensive nature, the sites included in the NAP may be expected to use a lower proportion of energy within steam systems than the sector as a whole. Although some uncertainties remain regarding the use of steam systems, the estimations do therefore appear to be broadly correct when compared to other data. Motor system energy use is predicted to be 16% of final energy demand by ECUK, this compares to 11% in the NAP measure. The NAP data predicts around 53% of electricity demand is for motors with the remaining going towards heating processes. This compares to 46% according to ECUK. As there is no electricity use assigned to lighting and other uses in the NAP data some discrepancy would be expected.

The different measures of final energy, primary energy and energy related GHG emission shown in Fig. 3-4, give an indication of the fuel split for each end use of energy. The biggest change seen between the measures is for motor systems, which become more significant when measured on a primary energy basis or by GHG emissions, due to the high proportion of electricity used.

3.3 TIME SERIES

Since the NAP data was collected changes in the overall energy demand of industry and the contribution of different subsectors could be expected. This is especially so given the economic downturn of recent years. This section examines these changes in energy demand and underlying reasons for the changes observed. Fig. 3-5 shows final energy demand taken from ECUK (DECC 2009c). The period is limited to 2001-2006. Methodological changes affect some subsectors from 2000-2001. Since 2007 data has not been provided on the same level of disaggregation (see Chapter 2 for details).

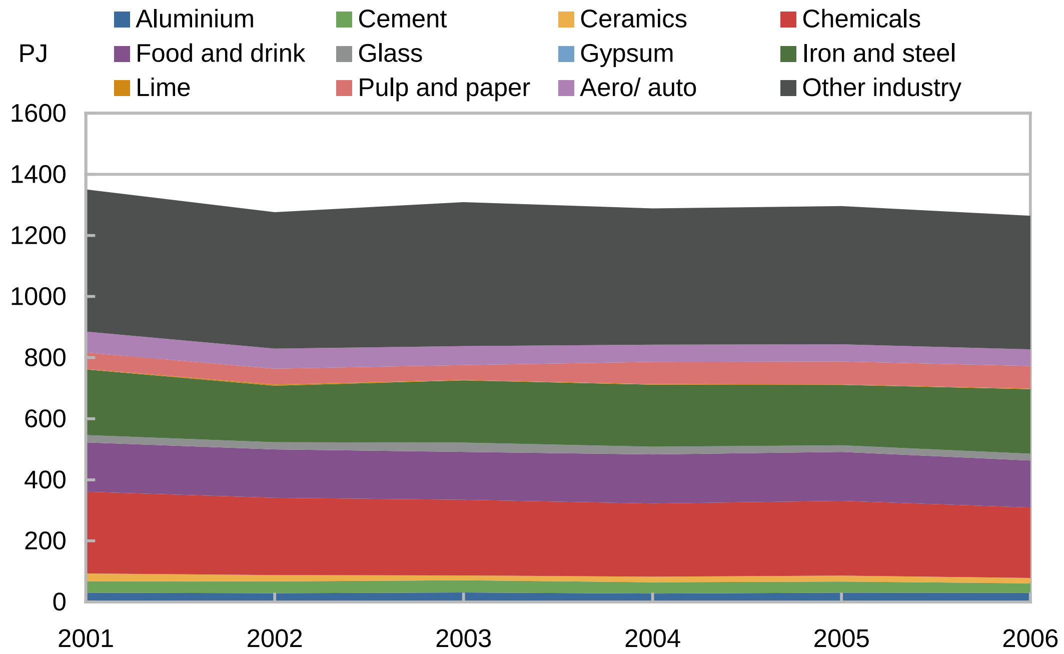

Fig. 3-5: Final energy demand from ECUK (DECC 2009c), 2001-2006, subsectoral split mirrors that used in the NAP database.

Fig. 3-6 shows primary energy demand by the NAP groupings from 2002-2010. This is based on information from the CCA TP5 report (AEA 2011b). The data is reported every two years. The 'Other' subsector is greater in ECUK data as it covers all energy use in industry, whilst not all sites are included in the CCAs.

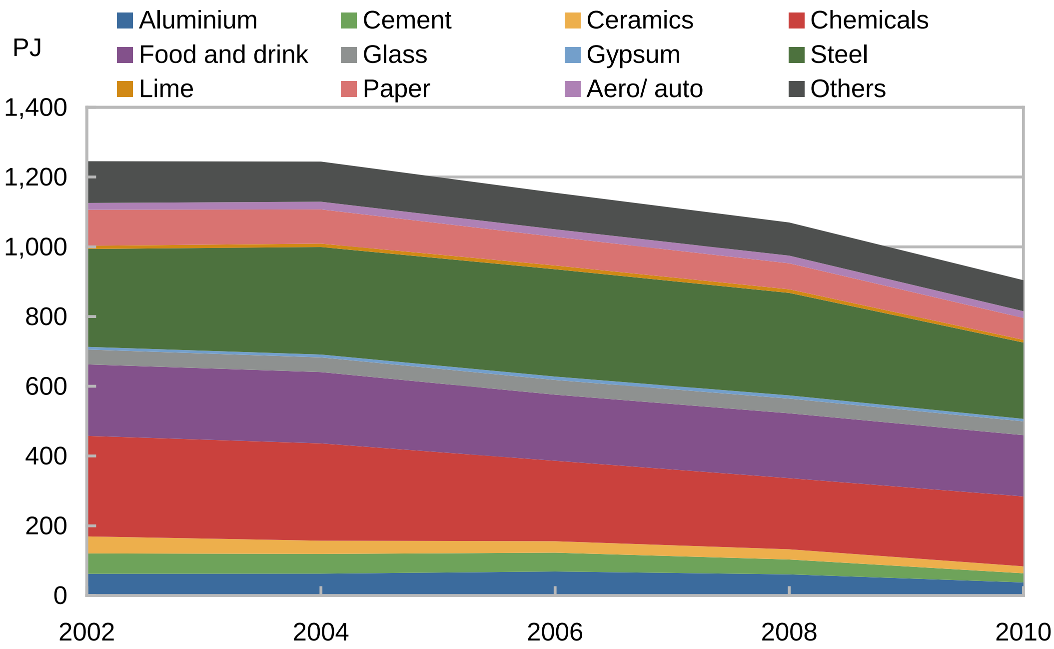

Fig. 3-6: Primary energy demand from CCA TP5 report (AEA 2011b), 2002-2010, subsectoral split mirrors that used in the NAP database.

Whilst Fig. 3-5 shows there was little change in either total energy demand, or the different subsectors' contributions up to 2006 more up to date information from ECUK (DECC 2011d)[12], shows total manufacturing energy demand has reduced by 20% from 2006-2010 with the greatest reduction from 2008-2009. Fig. 3-6 supports this. This fall is due, at least in part, to the economic recession experienced in the UK. Some large users of energy have ceased operations, the Teesside integrated iron and steel works was mothballed in February 2011 (Iron and Steel Statistics Bureau 2011), but has since changed ownership (SSI UK 2011), and the blast furnace was relit in April 2012 (BBC News 2012). There have also been plans to cut jobs and production at the Scunthorpe integrated iron and steel works (BBC News 2011). Additionally two of three Aluminium smelters have been closed, or closure is planned (BBC News 2009, Tighe 2011). There have also been closures in the Cement (Moore 2011) and Paper subsectors (Carbon Trust 2011b). Reductions in the energy demand of these subsectors can be seen in Fig. 3-6. The long term future of these plants and how much capacity other plants may change in response is uncertain.

Fig. 3-7 shows the variation in outputs from various subsectors, between 2002 and 2010. This is based on CCA data on physical output (AEA 2011b), except for the Chemicals subsector which is based on the index of production (Office of National Statistics 2012). All subsectors show a reduction in output from 2008-2010, as expected. The exception to this is the Food and drink subsector, which shows fairly constant output.

[12] The more recent data does not allow a disaggregation similar to that shown in Fig. 3-5, hence it cannot be included.

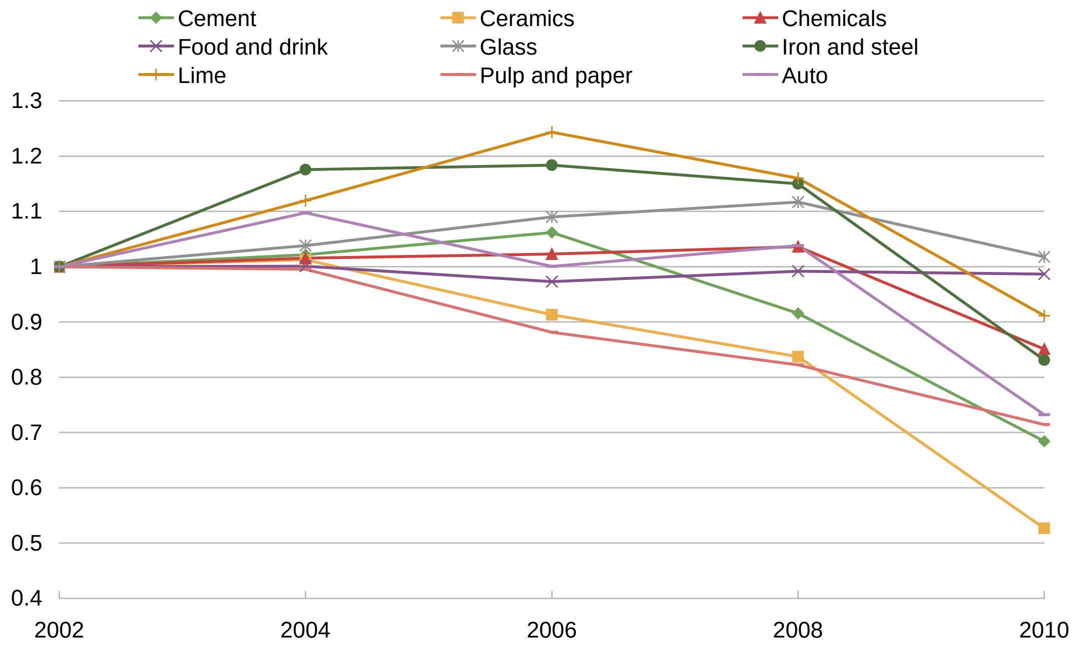

Fig. 3-7: Outputs 2002-2010, indexed to 2002. Data from CCA (AEA 2011b), the exception being Chemicals, which is based on the index of production (Office of National Statistics 2012).

Fig. 3-8 shows the specific energy consumption (SEC), that is the energy demand per unit of output, for certain subsectors. A decreasing SEC indicates an increasing energy efficiency, although other effects can also influence the SEC (see Chapter 2 and Chapter 5 for further discussion). The general trend of the subsectors in Fig. 3-8 is a reduction in SEC. When output reduces SEC may decrease as more inefficient plants are closed (there were closures in the Cement subsector over this time period and this likely influenced the considerable reductions in SEC seen, see Chapter 7 for further discussion of the Cement subsector). Alternatively decreased production may lead to increased SEC as plants are run at low capacities (as appears in automotive manufacturers), causing suboptimal energy performance. The relationship between measures of energy efficiency and output are further discussed in Chapter 5.

Based on the above discussion the energy demand represented by the NAP data will have decreased in recent time periods. This should therefore be considered when using the NAP data. Reductions in output have had an effect, as have improvements in the SEC (indicating an improving efficiency). Changes in industry energy demand can also be brought about by structural changes in industry. The relative size of different subsectors can change with time. Decomposition analysis can be used to examine the contribution of each of these effects. In Chapter 5 a decomposition analysis is undertaken for the UK manufacturing sector, which includes the effect of changes in output, structure, energy intensity and the contribution of the fuel mix and emissions factor of electricity in determining energy-related GHG emissions. Chapter 5 also investigates the underlying causes of the changes seen.

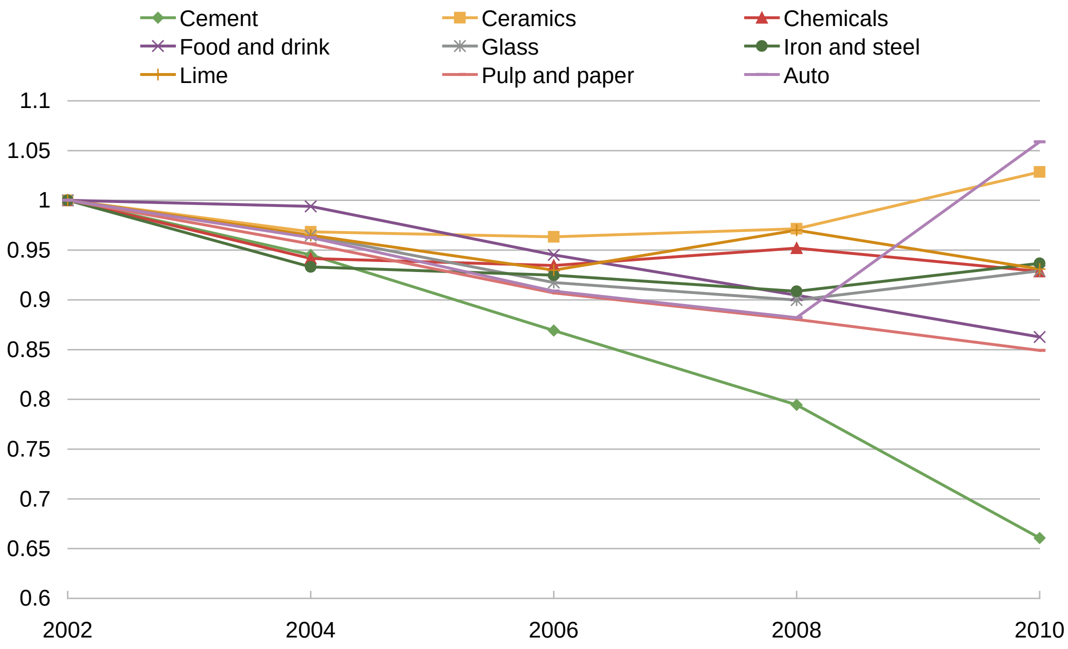

Fig. 3-8: SEC, 2002-2010, indexed to 2002. Reported or calculated from CCA data (AEA 2011b).

3.4 THERMODYNAMIC ANALYSIS

This section draws on work previously presented at the Fifth European Conference on Economics and Management of Energy in Industry (ECEMEI-5) in Vilamoura, Portugal during April 2009 (Hammond et al. 2009). This work comprises a thermodynamic analysis of the sites in the NAP database. This includes an energy analysis, and an exergy analysis. A copy of the paper is included in Appendix 6. The current author was the lead author and presenter of this work. The work as included here differs slightly due to an updated methodology. Background information on thermodynamic (energy and exergy) analysis can be seen in the paper and Chapter 2.

3.4.1 Energy analysis methodology

A first law analysis of the data was conducted utilising the information on end uses of energy in different subsectors.

3.4.1.1 Motor systems

Although the first law efficiency of a motor itself is usually high, at approximately 90% (Hammond and Stapleton 2001, US DOE 2004), the efficiency of motor systems can fall far below this. For example compressed air systems may have an efficiency of 15% and pump and fan systems 60% (US DOE 2004). For each sector the expected overall efficiency of the motor systems is estimated, based on a study by the US Department of Energy (2004). The figures used are detailed in Appendix 4, and vary from 29-60%. These figures may be optimistic, another study of motor systems (McKane and Hasanbeigi 2011) found an average efficiency of 40% for pump and fan systems, and just 6% for compressed air systems.

3.4.1.2 Heating processes

The useful energy out of a heating process is defined as the heat delivered to the product for the purposes of processing. Losses occur through conversion of the fuel to heat, through the structure, in stack gases and through other means. The efficiency as used here does not account for losses due to the cooling of the product after heating. It is difficult to determine the heating process efficiency for each subsector for a number of reasons. A range of different processes may occur at each of the sites, including steam systems and direct heating processes. Defining the useful output is not always straight forward, for example the slag from a blast furnace may be considered a waste product, but a proportion is utilised for road construction and as a material substitute for cement. Whether to define the unrecovered heat in the slag as waste is not a simple matter and could be seen to be dependent on the system boundary of the study. Finding studies undertaken for each subsector that could represent a 'typical' plant was not viable for an indicative study of the entire industrial sector.

A more general approach was therefore taken to the efficiency of heating processes. The split of the heat demand of each sector into five temperature bands was used as the basis for the analysis of heating processes. For each temperature band the amounts of electricity and fuel used were calculated based on the assumption that the electricity demand was utilised in supplying the highest temperature possible and that the heat supplied by CHP was used to supply the lowest temperature possible. This is an assumption, which it was felt would give sufficient accuracy for the purposes of the study. Other fuels made up the remainder of the demand. For the lowest two bands (temperatures less than 500°C) it was assumed that the heat demand was for steam systems. These assumed a boiler efficiency of 80% and an overall system efficiency (including the boiler, distribution and conversion losses) of 55% (IEA 2007, US DOE 2004). For heating processes above 500°C efficiencies of 70% for electrical and 50% for fuel heating processes were assumed. The efficiencies above 500°C were consistent with many previous studies conducting a thermodynamic assessment of the industrial sector (Hammond and Stapleton 2001, Reistad 1975, Rosen 1992, Utlu and Hepbasli 2007).

3.4.1.3 CHP systems

All CHP plants were assumed to have an overall efficiency of 75%, which is representative of a range of possible CHP technologies and operating conditions (IEA 2007), this relates to the conversion of fuel to heat and electricity. It was assumed that the heat was utilised in a steam system and so a further efficiency of 73% was applied to the heat output to account for distribution and conversion losses (in line with the losses in steam systems discussed above).

3.4.1.4 Exergy analysis

The thermodynamic quality of fuels was taken as unity, which is approximately true (Reistad 1975) and accurate enough for the purpose of this work. The thermodynamic quality is also unity for electricity and mechanical energy output. Heating processes were modelled as a heat transfer process taking place at the demand temperature, hence equation (2-5) was used to calculate the thermodynamic quality of the heat output. The calculated thermodynamic qualities can be applied to energy flows to convert into exergy terms. An environment temperature of 0°C was used for the quality factor calculations.

As the heat demands were not given at precise temperatures, but rather in temperature ranges, a method was required to calculate quality factors from the available information. For each of the temperature bands a single temperature was used to represent the heat demands in this band. In the bands that encompass a definitive range this was taken as the mid-point temperature, for the band less than 100°C a temperature of 60°C was used as this was estimated as a representative temperature of those demands less than 100°C. The temperature band greater than 1500°C is dominated by uses within the iron and steel sector for which more precise temperatures were known (McKenna 2009). The vast majority of temperature demand greater than 1500°C is therefore known to be between 1500°C and 1600°C, a representative temperature of 1550°C was used to calculate the exergy factor.

3.4.2 Results

The flows of energy and exergy through the manufacturing sector, as modelled in the NAP, are shown in Fig. 3-9, using Sankey and Grassman diagrams. Table 3-3 gives the energy demand, energy efficiency and exergy efficiency in each of the subsectors. The energy and exergy efficiency of industry on a final demand basis was calculated as 51% and 34% respectively.

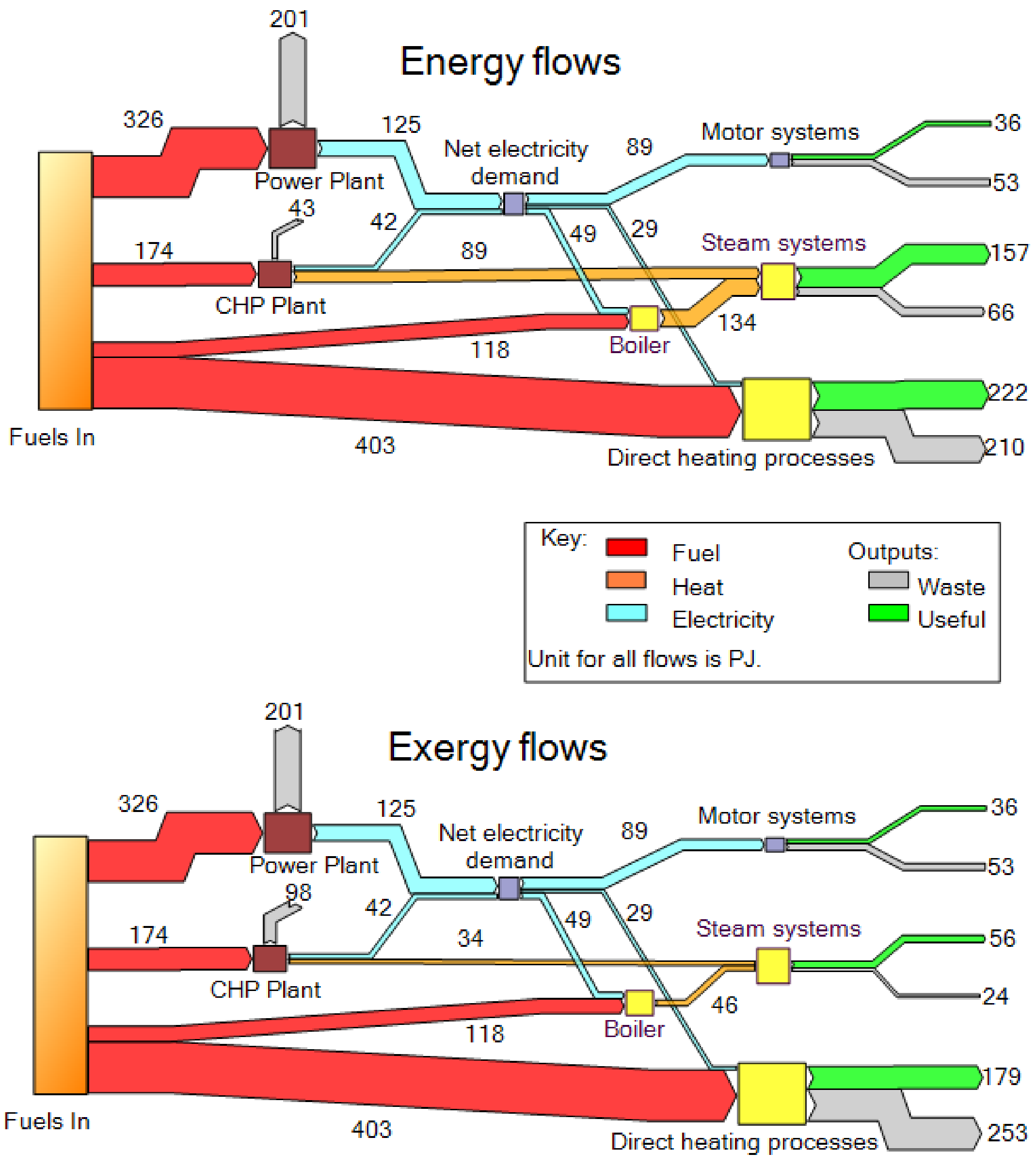

Fig. 3-9: Sankey (top) and Grassmann (bottom) diagrams showing annual flows of energy and exergy (in PJ) through the industrial sector according to the NAP database.

	Primary energy basis			Final energy demand basis		
Sector totals	**Demand (PJ/yr)**	**η (%)**	**Ψ (%)**	**Demand (PJ/yr)**	**η (%)**	**Ψ (%)**
Aluminium	55	30	21	26	64	45
Cement	53	43	35	44	52	42
Ceramics	24	42	34	19	53	42
Chemicals	233	42	26	197	50	30
Food and drink	121	41	18	91	55	24
Glass	30	47	35	28	50	37
Gypsum	17	38	18	12	56	25
Iron and steel	286	42	36	248	49	41
Lime	17	49	38	16	51	39
Pulp and paper	134	36	16	90	53	24
Aero/ auto	35	38	15	25	54	21
Other industry	17	38	17	12	54	23
Total industry	**1021**	**41**	**27**	**807**	**51**	**34**

Table 3-3: Demand and efficiencies, both energy (η) and exergy (Ψ), of main subsectors, based on thermodynamic analysis.

3.4.3 Discussion

The efficiencies shown in Table 3-3 and represented in Fig. 3-9 are indicative only and there are limitations in what can be inferred from these results The efficiencies shown for heating processes are a combination of the temperature of heat demand, and the fuel used to supply this demand. The efficiency of motor systems is estimated based on the expected use of motor systems. The highest efficiency processes from a final energy perspective are therefore, in descending order, electrical direct heating processes, steam systems (including CHP heat), and fuel based direct heating. Motor systems efficiency varies depending on the subsector from 29-60%. Direct fuelled heating has a lower efficiency than steam systems only because of the higher temperature demands, at lower temperatures it would be expected to be more efficient than steam systems in the majority of cases. On a primary energy basis any electricity use leads to further losses, with electricity from CHP representing a more efficient supply than centralised electricity production. When considering exergy heating processes cause further losses. Where higher temperatures are demanded these losses are less significant. This means that the Aluminium subsector, where energy use is dominated by high temperature electrical heating processes, has the highest energy and exergy efficiency on a final energy demand basis, but this drops considerably on a primary energy basis. The Iron and Steel sector, which has a large proportion of fuel based direct heating and a low motor systems efficiency consequently has a low final energy efficiency. This efficiency does not drop as considerably as other subsectors when exergy is taken into account as the majority of demand is at high temperatures. The lowest exergy efficiencies are found in those subsectors with low temperature demands (Food and drink and Aero/ auto being two examples).

This analysis indicates that from a primary energy (and also emissions) perspective electricity use is a poor choice in comparison to fossil fuels. The use of electricity is difficult to avoid in motor systems use and some heating processes however. Efforts are being made to decarbonise the electricity generation system, with a higher proportion of generation coming through renewable sources. If this continues it may become preferable to utilise electricity for heating processes traditionally fuelled by fossil fuels. This will exert more demand on the electricity supply sector however, which will already face a very difficult task in replacing the fossil fuel based system with a reliable low carbon alternative.

3.4.3.1 Comparison to other studies

Table 3-4 examines the energy and exergy efficiencies determined in other thermodynamic analyses of industrial sectors. These studies all use the approach of Reistad (1975), or similar (that is only including energy flows, not materials and other flows) and so are comparable to the present study. Schaeffer and Wirtshafter (1992), Rosen (1992) and Hammond and Stapleton (2001) carried out an analysis of the industrial sector as part of a larger economy-wide study. Utlu and Hepbasil (2007) undertook the study of the industrial sector in isolation. All the studies split energy use into process heating in three temperature bands and motor systems. The use of five temperature bands for each subsector in the current work, allowed a more accurate representation of thermodynamic quality, and so exergy. Schaeffer and Wirtshafter (1992), Rosen (1992) and Hammond and Stapleton (2001) all obtained similar values of energy efficiency and exergy efficiency, with Utlu and Hepbasil (2007) finding a similar energy efficiency, but lower exergy efficiency in their analysis.

The energy efficiency found in the present study (53% on a final demand basis, see Table 3-3) is generally lower than the results shown in Table 3-4. This is caused by the approach in estimating the efficiency of motor systems and low temperature heating (represented by steam systems) used in the present study. Here whole system losses have been represented rather than just those in the motor or boiler. For other studies typical efficiencies of 90% for a motor and 60-65% for lower temperature heating processes were used (Utlu and Hepbasli 2007).

The ratio of exergy efficiency to energy efficiency can give a good basis for comparison of the differences, due to exergetic considerations, seen between the studies. The value from the current work 0.67, is similar to that for Schaeffer and Wirtshafter (1992), Rosen

(1992) and Hammond and Stapleton (2001). The small differences seen between the result from the current work and those of Rosen (1992) and Schaeffer and Wirtshafter (1992) could partly be explained by the dead state temperature employed. A lower value (0°C) was used in the current study, in comparison to the majority of the other studies (25°C, see Table 3-3). Using a lower dead state temperature meant that a greater exergy efficiency would be calculated, for a similar heating process. Utlu and Hepbasil (2008) investigated the significance of varying the dead state temperature on industrial exergy efficiency. They concluded that when varying the dead state temperature between 0°C and 25°C a change of less than 5% was observed in the exergy efficiency of the sector. The differences seen between the studies examined here is also likely caused by a difference in the proportion of each end use in the country's industrial sectors. There is very strong agreement in the ratio of exergy to energy efficiency between the current work and the study of Hammond and Stapleton (2001). Similar dead state temperatures were used and in both cases the UK industrial sector is the focus, although the studies focus on different time periods and Hammond and Stapleton (2001) take a much broader approach to their analysis, with the work on the industrial sector being part of an economy wide exergy analysis. The study by Utlu and Hebasil (2007) found a significantly lower ratio of exergy to energy efficiency, again a small proportion of the difference could be due to a different dead state temperature. Utlu and Hepbasil's (2007) analysis had a similar proportion of motor use (13%) compared to here (11%), the difference therefore suggests that the temperatures of heating processes in the UK industrial sector are greater than in the Turkish industrial sector, as modelled by Utlu and Hepbasil (2007).

Author and publication year Country and study year	**Hammond and Stapleton (2001)** UK Mid 90s	**Rosen (1992)** Canada 1986	**Schaeffer and Wirtshafter (1992)** Brazil 1987	**Utlu and Hepbasil (2007)** Turkey* 2003
η (%)	69	68	71	66
Ψ (%)	46	41	43	30
Ψ/η	0.67	0.60	0.61	0.45
T_0 (°C)	-1	25	25	25

Table 3-4: Results from previous energy and exergy studies of industrial sectors. All efficiencies are on the basis of final demand.
***indicates an industrial sector specific study.**

3.5 IMPROVEMENT POTENTIAL

Improvement potential can be assessed, from a top-down perspective, by examining cross-cutting technologies. That is technology options that are not specific to a subsector of industry, but rather, can be widely applied. The above analysis has indicated that there are considerable inefficiencies in UK industry associated with steam systems and motor systems. Opportunities for reducing these inefficiencies, along with the increased use of combined heat and power (CHP) technology are assessed in this section. These opportunities are all applicable to multiple subsectors in manufacturing. The assessment here focuses on technologies that are currently available, or will likely be in the near term (before 2020). There are additional opportunities that apply to multiple manufacturing subsectors these are not examined in detail here, but are listed below. This list is not exhaustive, but covers the majority of current cross-cutting opportunities. Only those opportunities considered within the scope of the thesis are discussed, so product substitution, for example, is not included here.

- **Behaviour change:** Simple, no-cost measures such as turning off equipment whilst not in use can often save energy. Not applying best practice in terms of operation and maintenance can also considerably limit the performance of some equipment. The opportunities available through behaviour change can be difficult to assess quantitatively.

- **Space heating and lighting:** the focus of the current work is on industrial processes. Space heating and lighting are both considered building services not specific to the industrial sector and are not examined here (although space heating improvements will have some cross-over with those of steam systems).

- **Heating processes:** although heating processes are often process specific and so need to be assessed in a bottom-up manner there are certain best practices that can be widely applied. These include (European Commission 2009):
    - Reducing the temperature of flue gases, by air and product preheating (linked to heat recovery, discussed below).
    - Reducing the mass flow of flue gases, by reducing excess air.
    - Control of burners
    - Appropriate fuel choice
    - Oxy-firing, that is using oxygen rather than air in the combustion process
    - Improving insulation
    - Reducing losses through the furnace, for instance closing openings.

- **Heat pumps:** this technology shows considerable potential to improve the efficiency of low temperature heating, and when coupled with low carbon electricity generation can give significant emissions savings. Opportunities for utilising heat pumps are discussed within Chapters 6 and 7.

- **Heat recovery:** there are opportunities for increasing heat recovery throughout the manufacturing sector. To examine the whole sector in this manner required considerable work and is the subject of Chapter 6
- **Carbon capture and storage (CCS):** there are opportunities for this technology in multiple subsectors of manufacturing, which are all large users of energy. As this technology does not improve efficiency however it is not discussed in detail here. Element Energy (2010) provide an analysis of the potential for this technology in UK industry.
- **Fuel switching:** improvements on an emissions basis can be offered by switching to biomass fuel, waste or electricity (assuming a decarbonisation of the electricity sector). The potential for this switching is highly dependent both on the current fuel used, the available supply of alternative fuels and the ability of processes to use alternative fuels. There have been some favourable reports on the potential for fuel switching, AEA (2010b) estimated half of industrial heat demand could be met by biomass in the 2020s, being mainly used in boilers, with a smaller amount fuelling CHP systems. At higher temperatures where solid biomass is not suitable biogas has potential, especially in those industries that require a clean fuel (glass and ceramics), a high calorific value (metal melting) or natural gas as a feedstock (plastics) (DECC 2012h). As fuel switching is focussed on an emission reduction rather than an efficiency improvement it is not discussed further here.
- **Cooling systems:** conventional, compressor-driven, refrigeration improvements are discussed within the motor systems section below. Other opportunities in using alternative technologies and reducing cooling demand through energy management techniques are not covered. Refrigeration forms a significant proportion of final demand within the Food and drink and Chemicals subsectors (see Fig. 3-3).

3.5.1 Motor systems

Motors themselves are often of good efficiency (approximately 90%) in terms of turning energy (normally electricity) into shaft movement, when running at their rated power. Considerable efficiencies can arise from their misuse however. When considering the system rather than just the motor efficiency drops, as discussed in section 3.4.1.1. Improvement potential is often specific to the type of motor system, however there are a number of good practices that can be widely adopted (IEA 2007):

- **Matching the motor to the demand.** Motors are often oversized at the design stage (IEA 2009) to ensure a safety margin in meeting the load, or are sized to meet the maximum requirement for a variable load. The power demand of a motor varies with the cube of the rotational speed, so small changes in the required speed can lead to substantial energy savings (IEA 2009). Reducing the resistance to fluid flow is key to pumps, fans and compressed air systems (European Commission 2001). Improvement potential can include control strategies to respond to variations in load. Speed control devices such as adjustable/ variable speed drives (ASDs/ VSDs) are applicable in some cases.

- **Reducing the demand for motor power,** for example by replacing a compressed air demand with a blower [compressed air is a very expensive form of energy and in many applications replacing its use with an alternative can save in excess of 50% of energy (FDF 2008)], or turning off inactive equipment.
- **High efficiency motors.**
- **Improved maintenance,** with important areas being, filters, valves, leaks and lubrication.
- **High efficiency transmission systems.**
- **Reducing systems losses,** eg. reducing pipe friction in a pumping system.

Further specifics on the methods to save energy, including opportunities for pump systems, fan systems and compressed air systems can be found in a number of publications [for example (IEA 2007, McKane and Hasanbeigi 2011)]. Potential cost effective savings in motor systems, through a variety of measures are thought to be around 15-25% of current demand using a range of energy efficiency measures (IEA 2007, 2009, Worrell 2004). High efficiency motors, represent around 10% of energy efficiency savings in motor systems (IEA 2009). Much of the potential is therefore from optimising the system.

Fig. 3-10 shows how energy use within the umbrella of motor systems is split between different uses within UK industry, according to a study relating to 2003 (Market Transformation Programme 2003). In comparison to data from ECUK (see Fig. 3-4) a smaller proportion of motor system use is predicted to be used by Compressors and Chillers in the MTP dataset. (DECC 2010d). This may be as fans and pumps often comprise part of a refrigeration system but are classified separately by MTP. The MTP data is used here to inform further analysis due to the greater disaggregation of end uses[13].

[13] The MTP data was not disaggregated into subsectors at a high enough level to inform the thermodynamic analysis in section 3.4, but on a whole sector level was thought to be more accurate than that used for the thermodynamic analysis, which is based on data for the US (US DOE 2004).

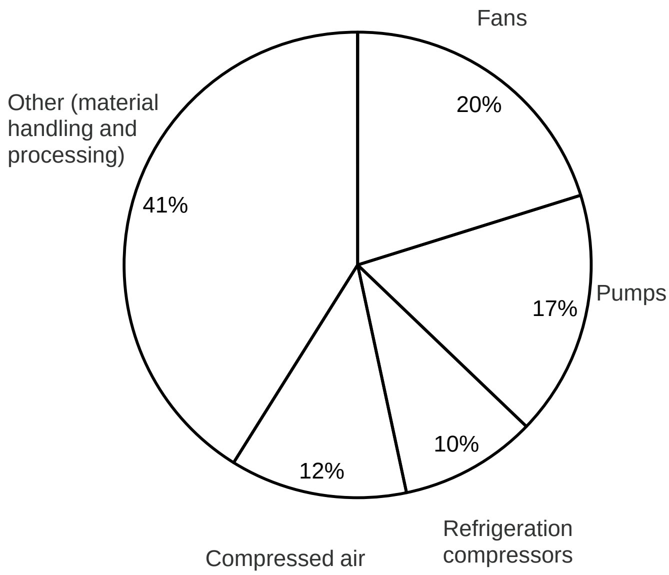

Fig. 3-10: Energy use within motor systems (Market Transformation Programme 2003).

To estimate the improvement potential for motor systems in UK industry the savings potential for pump, fan and compressed air systems were estimated using information from a study by McKane and Hasanbeigi (2011). The cost-effective savings and technical savings estimated are shown in Table 3-5. These are based on a detailed assessment of the potential for various technologies and the current rate of efficiency for the various systems in the EU. For the current assessment of improvement potential the cost effective savings potential is used. However a range is employed to the estimation of improvement potential, to represent the uncertainty in any such estimate. The improvement potential from pumps, fans and compressed air systems are therefore assumed to be 25-35%, 23-33% and 23-33% respectively. The methods of improvement in the pump, fan and compressed air systems are often based around good maintenance and control (McKane and Hasanbeigi 2011). The purchase of new equipment is another option, which is more capital intensive.

Technology	Cost effective savings (%)	Technical savings (%)
Pumps	30	44
Fans	28	29
Compressed air	28	38

Table 3-5: Cost effective and technical savings possible in industrial motor systems in the EU (McKane and Hasanbeigi 2011).

Improvements in refrigeration compressors are typically 25-35% at zero or low cost, through control and design (Carbon Trust 2011c). Taking into account that some sites will have previously taken these measures to improve performance in this manner a conservative estimate of 15-25% is used here to represent the improvement potential. Estimating the improvement potential in the 'Other' uses of motor systems including material handling etc. is more difficult, it is estimated as 15-25% here.

Using the split of energy use within motor systems shown in Fig. 3-10, and the savings potential discussed above overall savings from motor systems are estimated at 20-30%. This represents 18-27PJ/yr including those sites in the NAP and 34-50PJ/yr when using the ECUK measure of energy use (including all sites in 2008). Energy efficiency improvements to motors can be very cost effective due to the substantial operating times of motors. The average number of operating hours for an industrial motor system in the US is 5000hours/yr (Institute for Industrial Productivity 2012) (this gives a load factor of almost 60%). A motor that costs $2000 may use $50,000 of electricity during its lifespan (IEA 2007) and the purchasing of a high efficiency motor can be paid back in three years (IEA 2007). The cost-effective improvement potential would not all be expected to be realised, due to additional barriers to realising energy efficiency (see Chapter 4 for a fuller discussion of barriers). Conversely however, this identified potential is thought to be conservative being based on relatively easy, cost-effective, improvements to existing systems (the so called ‘low-hanging fruit’). As an example of what can be achieved when efficiency is a focus of system design an air conditioning system (that uses fans, pumps and compressors) can be designed to use 65-70% less energy than a conventional system (Von Weizacker et al. 1997). By considering each component and the underlying reasons for inefficiency these savings are achieved whilst providing improved comfort, taking up less space, improving reliability and having a lower cost (Von Weizacker et al. 1997).

Additional improvements to motor systems can be considered by widening the focus beyond the isolated motor system. Heat recovery from motor systems is often possible, especially from compressors and refrigeration systems. The heat of compression is typically 80% of energy input to an air compressor (McKane and Hasanbeigi 2011) and is a large source of inefficiency if not recovered. As refrigeration systems are designed in order to remove heat they are also well suited to recovery of this heat. Heat recovery is considered in detail in Chapter 6.

3.5.2 Steam systems

A steam system consists of steam generation (a boiler), steam distribution (pipework, valves) and energy conversion (heat exchangers). Steam systems in US industry were found to have an average efficiency of approximately 55% (US DOE 2004), a similar value would be expected for UK industry. On average 20% of the energy input is lost in the boiler, 15% in distribution of the steam and 10% in converting the steam energy to other forms (US DOE 2004). There is obviously considerable variation is these figures, thermal efficiency of the boiler unit can vary from 55-85% depending on the age of the boiler and fuel used (US DOE 2004). The distribution losses of the steam depend not just on the insulation levels and equipment used, but also the size of the site and the distances steam is transported. The conversion losses are partly dependent on the final use of the steam. Despite these variations there are a number of options to improve the performance of a steam system that can be applied to many systems. These are presented here, and are split into low and medium cost options for the boiler and opportunities relating to the steam system. The options listed here are based on information from a number of sources (Carbon Trust 2007, FDF 2008, IEA 2007).

Low-cost savings involve monitoring energy use and efficiency and undertaking basic maintenance to preserve performance.

Medium-cost savings involve the purchase of new equipment, these include:

- **Flue-gas heat recovery:** the recovered heat can be used in pre-heating combustion air, or feed-water (using an economiser).
- **Installation of a flue gas damper:** this prevents heat loss through the flue when the boiler is on standby.
- **VSD motors:** boilers often have a forced draft combustion air fan. Similar savings can therefore be made as detailed above in reference to motor systems. Replacing the fixed speed motor with a variable speed drive can offer significant savings.
- **Maintaining high levels of insulation** around the boiler and other components in the steam system.
- **Treating water** to remove substances that can reduce efficiency and prematurely wear the boiler.
- **Optimise boiler blowdown:** boiler blowdown is the flushing of the boiler to remove deposited solids. Too frequent blowdown wastes energy, too infrequent leads to inefficient performance. Heat can also be recovered from the blowdown operation.

Options for the steam distribution system, rather than the boiler include:

- **Leak checking.**
- **Ensuring good insulation levels** throughout the system.
- **Identifying and removing redundant pipework.**
- **Steam traps,** used to remove condensate from the system, require regular maintenance or can lead to large losses if stuck open.
- **Condensate recovery.**
- **Decentralisation of the steam system.** If the system is used to transport steam long distances it may be more efficient to use two or more smaller boilers at different locations than one large centralised boiler. Similarly if different pressures of steam are required by different processes matching the supply and demand of steam by using multiple boilers can save energy.

When boilers are replaced more efficient units can usually be procured. As with all equipment it is important not to oversize these. A new boiler can reduce energy use by in excess of 25% (FDF 2008). A combination of the technologies discussed above, retrofit to an existing system can save 10-20% of energy use in developed countries (FDF 2008, IEA 2007). Using an improvement potential for steam systems of 10-25%, so encapsulating both retrofit and replacement opportunities, gives 16.7-41.7PJ/yr of potential savings in those sites in the NAP database and 38.4-96.1PJ/yr according to the ECUK dataset. This figure does not account for any improvement in the steam systems associated with CHP systems. Reducing demand for steam, by improving the efficiency of the process that utilises the steam produced can offer large savings from the steam system (IEA 2009), although generally requires a more bottom-up analysis. This indicates the importance of a holistic approach to energy efficiency. If the steam system was considered in isolation it may run efficiently in terms of supplying a given amount of steam, but could still be supplying more steam than is required. Therefore with a wider system boundary it may appear inefficient.

In some cases the best option for improving energy efficiency of a steam system is by replacing the steam system with an alternative (IEA 2007). At low temperatures a heat pump can be used (see Chapter 6 and Chapter 7 for a discussion of heat pumps). A CHP plant also offers considerable potential for improvement over a separate steam system and centrally generated electricity. Much potential for the use of CHP lies in replacing demand that is currently supplied by steam systems.

3.5.3 Combined heat and power (CHP)

Conventional power generation, that is the combustion of fossil fuel to produce heat, raise steam and drive a turbine, involves considerable inefficiencies. A modern combined cycle gas turbine plant (CCGT) has a First Law efficiency of perhaps 55% (Dyer et al. 2008) (with further losses involved in the transmission and distribution of electricity), greater losses arise from coal fuelled power generation. Much of the losses involved arise due to heat being rejected to the environment. A combined heat and power (CHP) plant (also known as cogeneration) makes use of the heat that arises during power generation, using it to meet a heat demand, so improving the overall energy efficiency of the plant. CHP plants require a relatively constant heat demand to operate successfully. Industrial processes can provide such a demand. In 2010 5.9GW_e of good quality combined heat and power (GQCHP) was installed in the UK (DECC 2012h), approximately 50% of this was within the manufacturing sector (DECC 2011c). The main opportunities to improve energy efficiency are through increasing the use of CHP, rather than improving the efficiency of existing installations, which is already thought to be high.

According to the NAP database three subsectors, Chemicals, Food and drink and Pulp and paper, dominate CHP usage (see Fig. 3-1), this is confirmed by DUKES data (DECC 2011c). CHP is primarily used to supply heat with a temperature up to 500°C (Thoennes 1995) and so could potentially supply a large amount of the heat demand in the lowest two temperature bands of the NAP database, replacing steam systems. Unsurprisingly the subsectors with significant CHP capacity are the same as those with the highest demand in the two lowest temperature bands however (see Fig. 3-2) and potential for further industrial CHP in the UK is thought to be limited by some studies (IEA 2007). However more optimistic results were found in a study by DEFRA (2007a) that investigated the economic potential to increase CHP usage from a baseline of 2005 to 2010 and 2015. The results from this study in relation to low and medium temperature CHP are shown in Fig. 3-11, alongside historical information on the use of CHP in 2005 and 2010 (DECC 2011c). The DEFRA study predicted potential for a 5.4GW_e increase in capacity by 2010 compared to 2005 and an additional 1.4GW_e by 2015 (DEFRA 2007a).

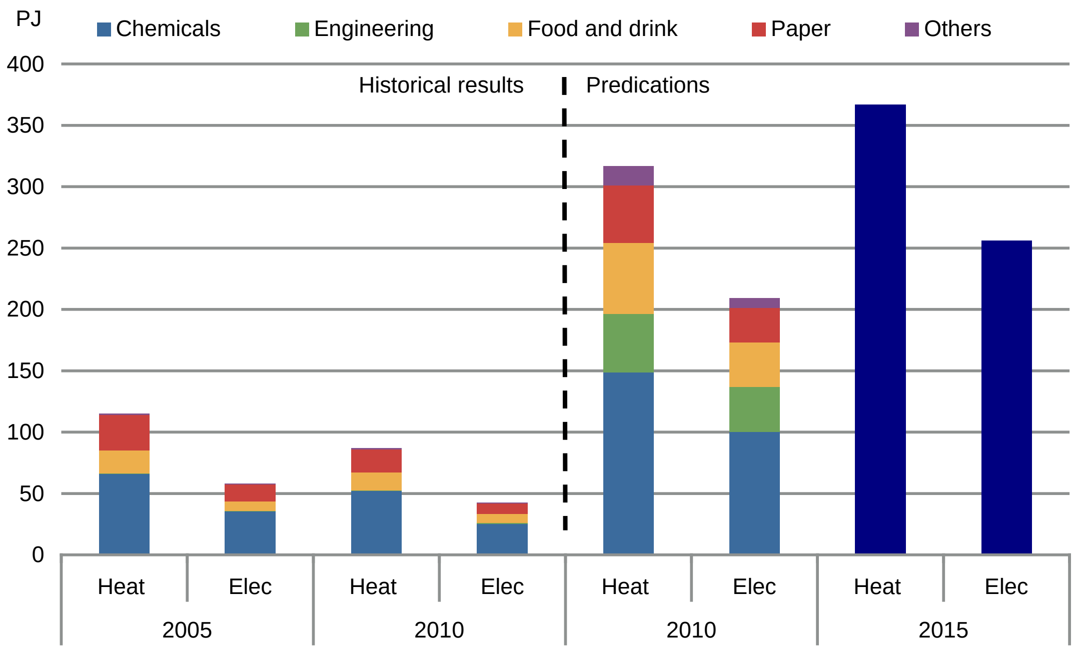

Fig. 3-11: Low and medium temperature CHP energy delivered (2005 and 2010) and predicted potentials (2010 and 2015). Historical data is taken from DUKES (DECC 2011c) and predicted data from DEFRA (2007a).

Fig. 3-11 shows the economic potential for increased use of CHP at low and medium temperatures. The results presented here are the upper bound of what would be possible, assuming a 100% take up rate of economic opportunities. This would not be reached in practice, but indicates the large economic opportunity offered by increased use of CHP. The increased capacity from 2010 to 2015 is due to expected growth in energy demand in the relevant subsectors of industry, with a similar subsector split expected in 2015. The analysis used a discount rate of 15% (DEFRA 2007a), this is fairly high for assessing an investment, and so required CHP plants to make a substantial return on their investment. Under a range of different energy price scenarios the additional economic capacity by 2010 varied between approximately 100 and 200PJ of electricity generated (DEFRA 2007a). Given the actual energy price increases seen the potential should be at the upper end of this range. CHP becomes more attractive for the investor when the 'Spark Gap' is large, this is the difference between the prices of electricity and gas (DEFRA 2007a). This is as most CHP plants run on natural gas and the electricity produced is sold back to the grid or used to save the purchase of grid electricity. Therefore a large spark gap (indicating a high electricity and low gas price) makes a CHP plant most attractive to the investor. Between 2005 and 2009 electricity prices increased by 64% and natural gas prices by 17% in the industrial sector (DECC 2010g) (this includes the Climate Change Levy). Therefore the spark gap has increased considerably and CHP should be a more attractive investment.

It can be seen from Fig. 3-11 that the economic potential identified has not been realised by a considerable margin. Between 2005 and 2010 the output from low and medium industrial CHP has actually fallen. This is not just a case of using the existing sites to a lesser degree. The number of CHP sites has fallen from 149 to 135, with capacity reducing from 3.0GWe to 2.8GWe.(DECC 2011c). The effect of the recession in closing existing sites (and those that may have shown potential for CHP), and discouraging investment in CHP plants, is likely to have been significant. CHP plants involve large amounts of capital investment and are often seen as risky (DEFRA 2007a). What this study therefore indicates is that there is a large unfulfilled potential for economic CHP plants, which is most likely to be reached with a growing manufacturing sector.

The broad technical potential for CHP usage was estimated using the NAP database. Site level heat demand data by temperature band was combined with information on CHP technology. CHP units are available for the industrial sector supplying a minimum of $40kW_e$ upwards (DEFRA 2007a). At a capacity of up to $1MW_e$ 50% of the heat is available at temperatures below 100°C. Above $1MW_e$ all the heat is available at higher temperatures (DEFRA 2007a). Up to 500°C was assumed to be supplied through CHP. Overall efficiency was estimated at 75% overall efficiency (IEA 2007), and heat-to-power ratio at 2:1 (DEFRA 2007a). These characteristics are fairly conservative, they are summarised in Table 3-6. It is assumed if the site has a sufficient source of heat it is suitable for a CHP plant. Lack of electricity demand is less of a constraint as excess electricity can be exported to the grid. The results from this analysis are shown in Fig. 3-12. The extra CHP plant capacity represented here is $2.3GW_e$. According to this broad analysis almost all heat demand under 500°C can be fulfilled by CHP, the remaining potential unsuitable for supply by CHP was less than 2PJ. Similar subsectors were identified with the greatest potential for CHP as in the DEFRA analysis shown in Fig. 3-11. This technical potential, shown in Fig. 3-12 is not as great as the economic potential identified in Fig. 3-11. This indicates that even in those smaller sites not included in the EU ETS there is considerable economic potential for CHP. The overall predicted increase in CHP capacity, $2.3GW_e$ for those sites in the NAP and $5.4GW_e$ according to the DEFRA study appears substantial when the 2010 installed capacity in the industrial sector stands at $2.8GW_e$ (DECC 2011c). Recent work by DECC found that by 2020 there is thought to be established technical capacity for $24GW_e$ of CHP, much of it within the industrial sector (DECC 2012h).

Parameter	Value
Minimum CHP unit	40 kW_e
Thermal output 40-1000kW_e	50% <100°C, 50% < 500°C
Thermal output 1000kW_e+	100% <500°C
Heat-to-power ratio	2:1
Overall efficiency	75%

Table 3-6: Parameters of CHP plants used to assess the technical potential in UK industry.

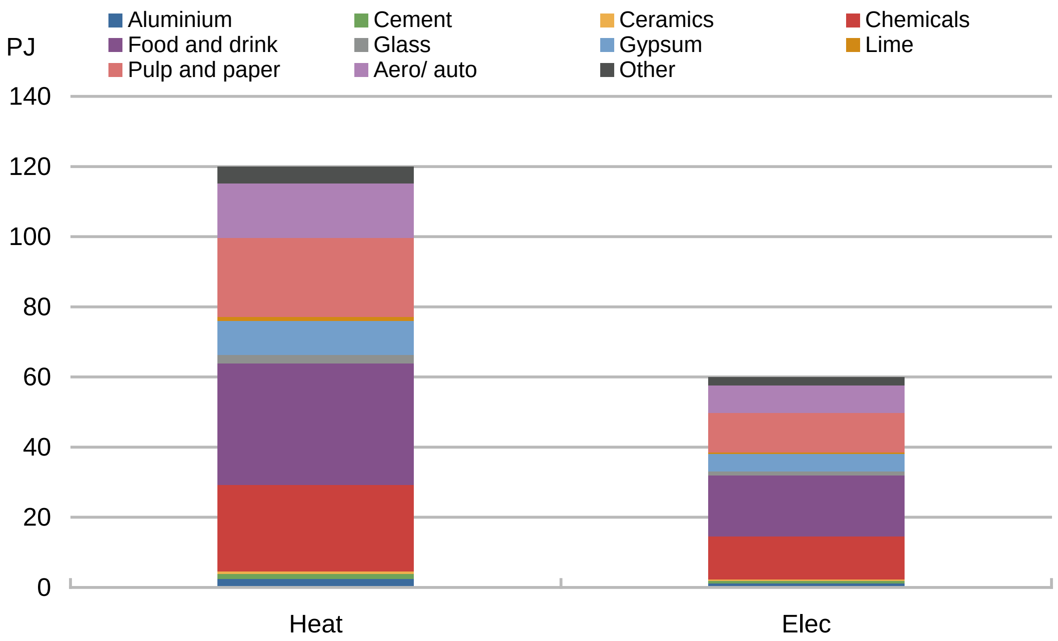

Fig. 3-12: Technical potential for CHP, assessed using NAP database.

The focus in this section so far has been on supplying temperature demands up to 500°C with CHP. There is thought to be a small potential to increase CHP usage in high temperature industries (metals and mineral products) and sugar production. 2005 CHP use in the steel industry generated approximately 1PJ of electricity, there is an estimated potential to approximately double this, with 0.48PJ of additional heating being cost effective in 2010 (DEFRA 2007a). No further potential for CHP in the glass and cement subsectors was identified in the same study. In the sugar sector there was thought to be potential to increase capacity slightly by expanding existing systems, an additional 0.55PJ of heat supply being cost effective in 2010. These high temperature opportunities comprise only 2% of the total identified additional CHP capacity (DEFRA 2007a).

The IEA (2009) lists the following as the criteria to determine if CHP is applicable at an industrial site (this applies to most sites). These are additional to the considerations regarding the technical viability detailed above:

1. A ratio of electricity to fuel costs of at least 2.5:1.
2. Annual demand for heating and/ or cooling (in the case of tri-generation) for at least 5000 hours a year.

3. The ability to connect to the grid at a reasonable price, with back-up and top-up power available at reasonable and predictable prices.
4. Space for the equipment and short distances for heat transportation.

The current level of costs in the non-domestic sector (including the Climate Change Levy) is 6.6-12.5p/kWh for electricity (average 8.98p/kWh) and 2.1-3.7p/kWh for natural gas (average 2.6p/kWh) (DECC 2012j). The required cost ratio will be met in the majority of cases. A heat load for 5000 hours a year implies a load factor of 0.57, most larger users of energy (such as those included in the EU ETS) would be expected to exceed this. When modelling the sites in the NAP to form the database used here the expected load factors used varied from 0.7-0.95. The third condition is best addressed with suitable policies, as has been done in Finland, leading to one of the most vibrant national CHP markets (IEA 2009). The fourth condition for applying CHP is site dependent and cannot be assessed for the sector as a whole.

There is also potential within industry for Combined Cooling Heat and Power (CCHP, or tri-generation), to also fulfil a cooling load at an industrial site (cooling demand is fulfilled by an absorption chiller powered by low temperature heat, see Chapter 6 for more details on absorption chillers). However the economics of additional cooling are marginal and the CHP installation would normally have to be justified based on the heat demand (DEFRA 2007a). So although greater energy savings may arise from tri-generation it is unlikely to increase the overall potential in terms of heat and power from CHP in the industrial sector.

Future potential for CHP includes the use of biomass and waste as fuels. Within the industrial sector process waste can be utilised in this manner, thereby potentially reducing fuel costs and waste disposal costs. An example of waste fuelled CHP exists within the Pulp and paper subsector (DECC 2012h). The use of anaerobic digestion (AD) CHP within the food and drink subsector also holds potential for using food waste. These different fuel options could reduce the carbon intensity of the energy supplied by CHP.

3.5.4 Discussion

The final energy savings, primary energy savings and GHG emission savings from implementing the improvement potential options in motor systems, steam systems and increasing the capacity of CHP generation are shown in Fig. 3-13. These were calculated based on the assumption that all motors were powered electrically and all steam systems were supplied by natural gas. CHP plants were assumed to be natural gas fuelled and operate with an overall efficiency of 75%, and replace natural gas fuelled boilers with an efficiency of 80%, and electrical generation with an efficiency of 55% (representative of a combined cycle gas turbine) and a transmission and distribution efficiency of 90%. These parameters are generally conservative in terms of predicting the amount of energy and emissions saved. Primary energy and GHG emissions are calculated using the conversion factors discussed in Chapter 2. Error bars are in relation to the uncertainty expressed above regarding the potential savings in relation to motor systems and steam systems. The motor and steam system savings are based on estimations that cover all of the industrial sector, rather than just those sites represented in the NAP database. The CHP potential savings are based on the 2010 economic potential estimated from the DEFRA study (DEFRA 2007a). No error bars are included for the CHP estimations. As discussed above, poor economic conditions may result in no further CHP installations due to high capital costs, whilst the technical potential for CHP is substantial.

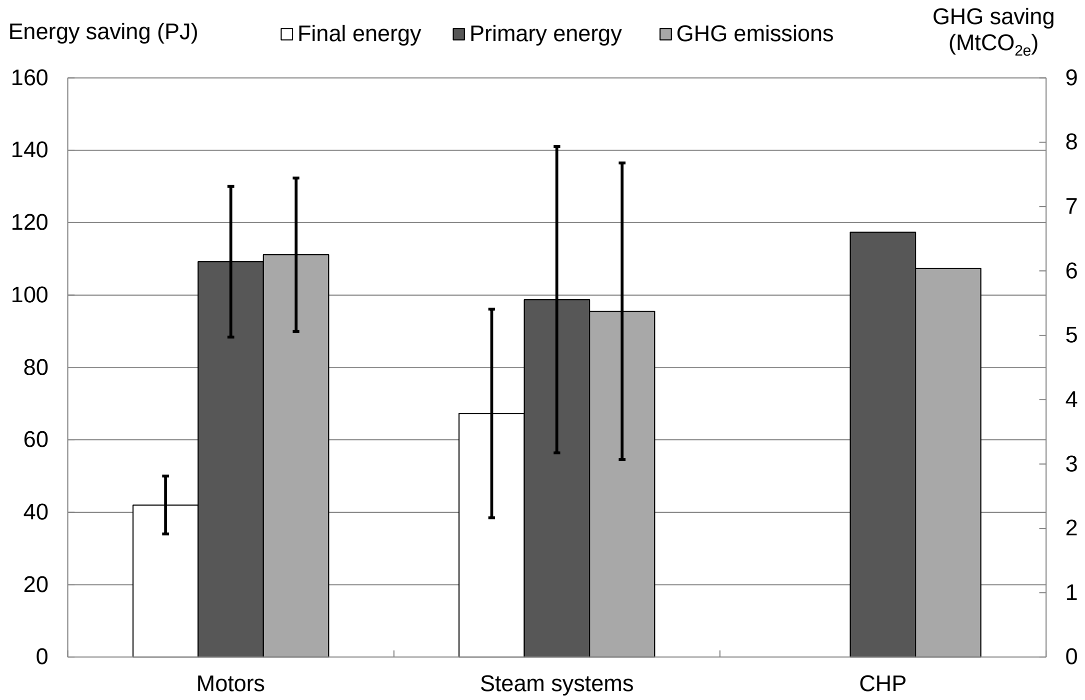

Fig. 3-13: Energy and GHG emission savings through cross-cutting improvement potential

Fig. 3-13 shows that the expected savings from the different cross-cutting technology options assessed here are of similar magnitudes, however there are different effects associated with each of the options. The domination of electricity in supplying motor systems means that they take on greater relative significance in comparison to fossil fuelled steam systems, when comparing primary and GHG emission savings, than when comparing final energy savings. Increasing the capacity of CHP systems obviously only makes sense from a primary energy and GHG emissions perspective as it is being compared to the current method of electricity generation. The use of CHP as above saves approximately 15% of primary energy compared to conventional generation. CHP is seen as a key component in reducing the emissions from industry by the current government (DECC 2012h). However, CHP fuelled by natural gas may be a transitional technology, to be replaced in the longer term with biomass fuelled systems, or alternative technologies, such as heat pumps (DECC 2012h). A largely decarbonised electricity sector is expected by 2030 (DECC 2012h), although some might consider this optimistic, and this would increase the attractiveness of electrically fuelled heating options. Natural gas fuelled CHP is likely to provide cost effective abatement until this time (DECC 2012h). As the heat generated through CHP will replace that currently supplied by steam systems, in many cases, the identified improvement potential of steam systems will decrease with the increased capacity of CHP. Fig. 3-13 shows the improvement potential through independent improvements

3.6 SUMMARY

A bespoke database (referred to as the NAP database) was constructed based on emissions data for those sites included in the EU ETS. The NAP data does not cover the whole manufacturing sector and is specific to the time period 2000-2003. However it has the advantage over publically available datasets of offering a user-defined disaggregation level. This presented the opportunity for more detailed information on energy use. Heat demand was estimated in defined temperature bands. The NAP database was used for analysis in the current chapter and is also built on in subsequent chapters, particularly in the assessment of heat recovery opportunities presented in Chapter 6. The energy demand of different subsectors in the NAP database was found to correspond well, in most cases, with other datasets. Where there was not good agreement between the sources a reasonable explanation could be reached. There was also shown to be good agreement in the end uses of energy between datasets. A thermodynamic analysis of the industrial sector based on the NAP database was carried out to illustrate the energy and exergy flows through the manufacturing subsector. The results from this in terms of the overall energy and exergy efficiency of the subsector were compared to similar studies, and found to agree to a reasonable level. Observed differences were caused by the parameters of the study, and the structure of different nations' industrial sectors. Energy use in recent time periods has been considerably affected by the recession and closures, or mothballing, of important sites has occurred. How this has affected the energy use throughout manufacturing was discussed.

The improvement potentials offered through cross-cutting opportunities related to motor systems, steam systems, and CHP systems, were examined. This suggested significant improvement could be achieved on current energy use. The magnitude of realisable potential in the near term is similar between the areas of motor systems, steam systems and the increased use of CHP plants. The potential for other cross-cutting improvement opportunities, specifically related to heat recovery, is examined in later chapters.

The top-down approach taken in this chapter has limitations. In UK manufacturing there will be substantial variation within each subsector, even where separate sites appear to use similar processes, there can still be variation caused by the age of the equipment, and the operating and maintenance procedures used at an individual plant. To gain more precise measures of energy demand and efficiency, studies need to be carried out on a more disaggregate level, focusing on a subsector of industry or even a single plant. However the work undertaken here still represents a valuable resource. The constructed database has a greater subsector disaggregation than most publically available data and is valuable in informing further work, highlighting where more detailed studies should be undertaken. The work of the current chapter provides an indicative indication of energy use and improvement potential.

CHAPTER 4

DRIVERS AND BARRIERS TO ENERGY EFFICIENCY

Chapter 3 discussed cross-cutting energy efficient technologies that can offer improvement potential in industry. However, often it is not the existence of a suitable technology that limits the energy efficiency realised. The uptake of energy efficient technology is determined by the drivers and barriers to energy efficiency that are discussed within the current chapter. Fig. 4-1 gives an indication of the actual energy savings realised, or market trend potential, in relation to the thermodynamic, technical and economic potential. The size of various bars is purely indicative and not based on any quantitative basis.

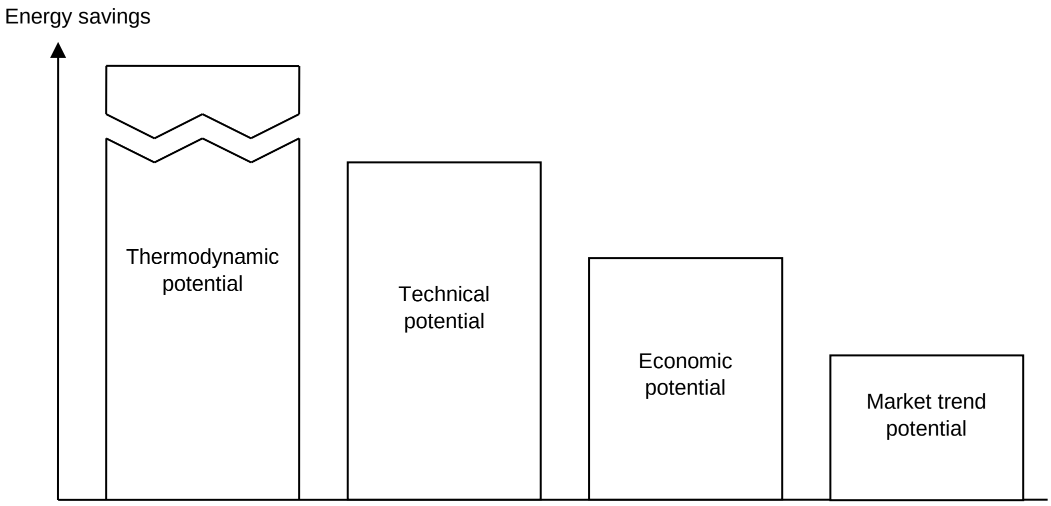

Fig. 4-1: Limitations on thermodynamic potential. Adapted from Jochem (2000) and Hammond and Winnet (2006).

With regards to Fig. 4-1:

- **Thermodynamic potential** is the absolute energy saving available according to the laws of thermodynamics, this will never be achieved in practice, but can often be approached. The IEA reports that globally *'the energy intensity of most industrial processes is at least 50% higher than the theoretical minimum determined by the laws of thermodynamics'* (IEA 2006).
- **Technical potential** is the next level of savings, it relates to what can be achieved with current technology (or what is thought can be achieved with future technology, the exact definition is dependent on the scope of the study). The availability of technology can therefore act as a barrier to energy savings. The difference between the thermodynamic and technical potential is the potential savings that could be offered by future technological advances (although the absolute limit of the thermodynamic potential will never be

reached). The fragmentation of the UK science base and fall in the number of Research, Development and Demonstration (RD&D) projects relating to industrial energy efficiency being implemented, is seen as a barrier to the technical potential (Future Energy Solutions 2005a). Fig. 4-2 shows the large decline in Industrial Energy Efficiency Research, Development and Demonstration (RD&D) funding in the UK since the 1970s. Public RD&D expenditure in general energy efficiency in the UK has increased hugely over the past few years reaching £123m in 2010 (40% of total energy RD&D expenditure) (IEA 2012). Only £5m of this was allocated specifically to industry, with the vast majority going to transport (£95m). Overall energy R&D in the UK is low as a percentage of GDP, being relatively less than in Germany, the United States, France, Canada and Japan (IEA 2010a). R&D funding is not sufficient by itself to encourage substantial efficiency improvements, but is an important component (when used correctly) of a successful energy policy (Garrone and Grilli 2010). The influence of RD&D programmes on energy efficiency in manufacturing is explored in a paper, included in Appendix 6, for which the current author was a co-author.

- **Economic potential** is defined as those measures for which the net present value is greater than zero over the lifetime of the project, although other definitions of economic feasibility may be used at the company level (see section 2.4.1). Measures that are not economic are very unlikely to be pursued. The economic potential is dependent on the capital cost of a project and the revenues it generates, which itself is dependent on the maintenance and operating costs, the energy saved, the energy price (and predicted future prices), any financial incentives such as a carbon tax and the discount rate used. The financial savings offered through the application of an energy efficient technology act as a driver to its adoption. The difference between the economic and technical potential is known as the welfare potential (Jochem 2000) and sufficient fiscal subsidies and/or penalties provided by policy can act as a driver to energy efficiency, closing the gap between the economic and technical potential.

- **Market trend potential** is what is actually achieved in practice, the difference between the economic and market trend potential is often known as the 'energy efficiency gap' (Jaffe and Stavins 1994), or 'energy efficiency paradox' (Van Soest and Bulte 2001). The reasons for the gap are large in number and diverse, they are comprised of the barriers discussed below, in section 4.1.2.

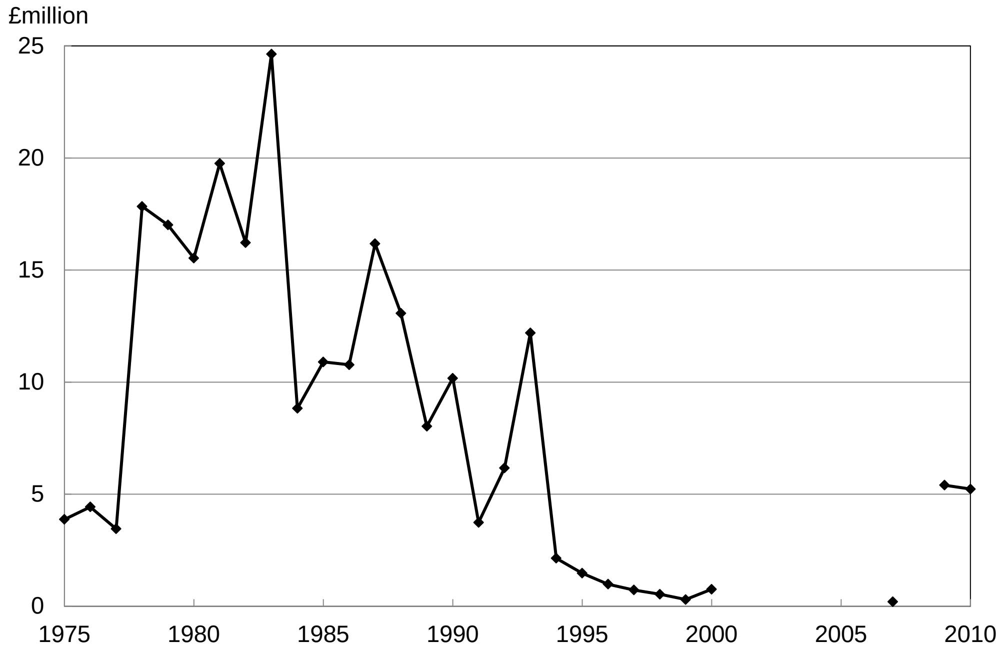

Fig. 4-2: UK RD&D spend on Industrial energy efficiency in 2010£, data is not available for all years (IEA 2012).

This chapter examines the main drivers and barriers to the adoption of energy efficient technology within industry, and the policies in the UK that aim to strengthen drivers, or reduce barriers, discussing their effectiveness and also future recommendations. There is a large variability in the way that energy use, and measures to improve efficiency, are viewed throughout the industrial sector. The industrial sector is split into two subsectors with stronger and weaker drivers to improving energy efficiency. This split forms a basis to better understand the effects that drivers can have on energy efficiency performance. This last section of the current chapter, the splitting of the sector, is included in published work (Hammond and Norman 2012a) that is included in Appendix 6.

4.1 DRIVERS AND BARRIERS

4.1.1 Drivers

Assuming that a given technology exists there are number of drivers that act to facilitate the uptake of the technology, increasing the economic and/ or the market trend potential. The following is a summary of these drivers:

1. **Energy-related financial savings:** reducing energy use obviously reduces costs to the company. These savings are usually the primary component of the return on energy efficiency investments. All other factors being equal the higher the rate of return on an investment the more likely that it will be implemented. The level of financial savings offered therefore determines the economic potential of a technology, and also influences the market trend potential. The more important energy use is to a company, financially, the stronger this driver can be. Energy costs in UK industry subsectors were found to vary between an average of 0.5% and 17% of the total costs of a subsector (see Fig. 4-4, below), and will have even wider variation at the individual company level. This driver can be strengthened by increasing energy prices.

2. **Legislation:** this can lead to further financial savings if the price of energy is increased through a carbon tax, or other mechanism. This can either reward energy savings, or penalise energy use and energy-related emissions. Legislation can also set standards for the minimum efficiency of certain technologies and so ensure their adoption. In some cases minimum efficiency standards can increase the market trend potential over what would otherwise be economic.

3. **Indirect benefits:** these include effects that are additional to energy saving when installing efficient equipment. They can include productivity increases, public perception of the company, and a more highly motivated workforce. These benefits are harder to quantify than direct energy savings and so are often not as persuasive to companies when assessing energy conservation projects. However, it has been suggested that these indirect benefits can often be greater than the direct energy savings (Pye and McKane 2000). Indirect benefits are not usually included in a calculation of the economic potential, but can increase the market trend potential. Public perception can be a very important driver for some manufacturers who wish to portray an environmentally conscious image as part of their product.

4. **Individual champions:** the existence within a company of an employee, with the ambition and long-term vision to improve energy efficiency, can be a key driver to energy efficiency, provided they are in a position where they can make or influence decisions (Rohdin and Thollander 2006). In some cases this can mean that even currently uneconomic measures are undertaken, with a view to higher energy and carbon prices or the indirect

benefits mentioned above. This means the market trend potential can exceed the economic potential in rare occurrences.

The drivers discussed here are interlinked. As energy prices increase and legislation to target excessive energy use becomes widespread the opportunities for saving energy become more widely recognised. This leads to the better understanding of indirect benefits and a greater existence of individual champions. As can be appreciated, all of these drivers to energy efficiency can vary greatly between subsectors of industry and companies within these subsectors. The expected variance in strength of drivers in different subsectors of industry inspired the split of industry into two subsectors for which the strength of drivers to energy efficiency would be expected to be stronger and weaker. This is discussed in section 4.3.

4.1.2 Barriers

Barriers exist that limit the technical potential and the economic potential of a technology. These can be very important, but are fairly straightforward, being related to the existence of a technology and its cost. This section examines the reasons for the 'energy gap' between the economic and market trend potentials, that is, why an energy efficiency technology is not used if it offers financial savings. Previous studies on barriers have often split the barriers that cause the energy efficiency gap into economic, behavioural and organisational classifications (Rohdin and Thollander 2006, Sorrell et al. 2004), further splitting economic barriers into market failures and market barriers (Jaffe and Stavins 1994). This sort of classification was avoided here, it can be difficult to classify certain barriers (Weber 1997), additionally the classification into market failures and barriers assumes a perfect and efficient market, which is not the case in practice, and can limit the ambition of policy, as traditionally energy policy only targets market failures (Palm and Thollander 2010). The barriers listed here are based on empirical studies, as cited. The barriers discussed are not universal and the importance, or existence, of each can vary with the size of company (Rohdin and Thollander 2006), sub-sector of manufacturing (De Groot et al. 2001) or due to intangibles such as the company culture. Due to the large diversity in the barriers those discussed here may not be exhaustive, but it is hoped the most significant are covered:

1. **Lack of information:** this can take different forms and so is further split.
    a. **Current energy use:** without sub-metering and an energy audit it is difficult to know the current state of energy use (Rohdin and Thollander 2006), and so difficult to target areas in which to conserve energy.
    b. **Opportunities:** without knowledge of the opportunities and how to analyse these opportunities for conserving energy a firm will not implement them.
    c. **Motivation:** information on why it is important to reduce energy use and emissions is important in leading to opportunities being realised.
2. **Focus on production:** companies will usually place energy issues at a lower priority than issues regarding production (Future Energy Solutions 2005a). This

is natural and understandable, after all a company is selling a product not an energy efficient production system. This focus on production can directly affect energy savings, for instance a heat recovery technology may not be used because of a fear of changing a process and altering the product. The focus on production can also indirectly be a barrier, being the cause of a lack of capital and time for energy efficiency projects (as discussed below). Generally if a company places sufficient focus on energy efficiency many of the barriers discussed here can be overcome.

3. **Lack of capital:** a company has a finite amount of capital to spend on a variety of projects. This available capital is primarily used for production issues, and those projects with the shortest payback times. This can mean that energy efficiency projects although economically viable, are not implemented (Future Energy Solutions 2005a).
4. **Lack of staff time:** this is linked to the focus on production. Staff are tied up in projects perceived as being most important (Rohdin and Thollander 2006) and cannot dedicate the time to energy efficiency issues. The use of external consultants can overcome this lack of time, but will incur additional costs that may themselves act as a barrier.
5. **Lack of staff skills and awareness:** if staff do have the time to dedicate to energy conservation projects, and have the information about energy use and opportunities they often do not have the skills to undertake analysis of energy efficiency options (Future Energy Solutions 2005a). Similarly to lack of staff time, external consultants can assist here, but bring additional costs.
6. **Hidden costs:** these may not be taken into account when calculating the net present value (or similar measure of economic viability) of a project, but may non-the-less be important in the decision for a company not to install efficient equipment (Rohdin and Thollander 2006). Examples are production disruption, overheads and staff costs in collecting and analysing information. Production disruption is often of great importance for energy-intensive processes, that run continuously, and may not be as significant for SMEs (Sorrell et al. 2011). It can be argued that these hidden costs should be included in determining the economic potential, but like indirect benefits they are hard to quantify. They are therefore not usually included in determining economic potential but are recognised as a real and significant barrier. Recognition of the potential of hidden costs may be a reason stringent investment criteria are required for energy efficiency projects (see point 7).
7. **Perceived profitability and investment criteria:** the payback time for implementation of a particular project varies by company but is typically 1-3 years for energy efficiency projects (Coito and Allen 2007, Rohdin and Thollander 2006). This payback period is strict in comparison to that used in general investments. This short payback times may be a way of compensating for hidden costs (Rohdin and Thollander 2006). It has been found that large firms were most likely to have strict criteria in place when it came to investment

criteria for new projects, whilst smaller companies often judged cases on their individual merits (Rohdin and Thollander 2006).

8. **Risk:** for the facilitator of an energy conservation project the consequences of failure are often greater than the rewards for success (DeCanio 1993) and so can deter involvement unless high rewards are offered (Future Energy Solutions 2005a, Rohdin and Thollander 2006). Fears about the performance of new equipment, especially in maintaining standards of production, comprise the most significant perceived risk. Risk related to future energy price is not thought of as important, as most companies are of the view that energy prices will rise over the long term (Rohdin and Thollander 2006). However Van Soest and Bulte (2001) suggest it may be advantageous for firms to delay investment in new technology as future technology may provide greater savings, this finding was not backed by any of the empirical studies reviewed however. Linked to risk is inertia, some individuals and companies are averse to changing a process or method of manufacture, even when potential benefits exist.

9. **Limited windows of opportunity:** lots of energy conservation measures require considerable time to install new equipment. Sites usually have a period of 'downtime' scheduled where maintenance is carried out and new equipment is installed. This is limited however, in order to maximise production and minimise costs (Future Energy Solutions 2005a). The priorities in the downtime will usually not be energy conservation measures, due to the focus of production. If extra downtime is needed to install energy conservation measures it leads to additional costs and so makes the investment less attractive. The biggest window of opportunity is when a site is refitted and new equipment is purchased, this can partly overcome the barriers of hidden costs and lack of capital. These factory refits do not occur frequently however, when they do the opportunity should be maximised, by installing the most energy efficiency equipment available.

10. **Split incentives:** this can take two forms, between site users and owners or between the instigator of a project and the profiteer. When premises or equipment are not owned by the company operating them there is confusion about who pays for improved equipment (Rohdin and Thollander 2006), it is similar to the problem between the tenant and landlord in a rented property. The issue exists internally in companies when another department to the instigators will profit from the energy conservation measures (Rohdin and Thollander 2006). Similarly when managers move roles within the company every few years, unless payback time is very short others may get the reward for their work (DeCanio 1993). It should be recognised that a company is not a single entity, that acts in the most economically rational way, but a group of individuals, who behave as individuals (DeCanio 1993).

The strongest barriers of those discussed above recognised by previous studies are focus on production, hidden costs, and lack of information (De Groot et al. 2001, House of Commons Committee of Public Accounts 2008, Rohdin and Thollander 2006, Sorrell et al. 2011, Sorrell et al. 2004). Lack of information is consistently cited as one of the main barriers, particularly lack of sub-metering (House of Commons Committee of Public Accounts 2008, Rohdin and Thollander 2006). Lack of information is generally a greater problem for the non-energy-intensive subsector of manufacturing, for whom energy use is not of as great importance as for the energy-intensive industries (Sorrell et al. 2011). There is some disagreement over the strength (or existence) of lack of capital as a barrier. Rohdin and Thollander (2006) and De Groot et al. (2001) found lack of capital not to be a significant barrier if other barriers were overcome, if a project was decided to be worthwhile capital would be found. A study by the House of Commons Committee of Public Accounts (2008) did find lack of capital cited as a significant barrier when assessing why carbon savings identified by the Carbon Trust were not made however. Sorrell et al. (2011) found hidden costs and access to capital were the main barriers in an extensive survey of barriers to industrial energy efficiency with access to capital most significant in relation to SMEs. As already discussed lack of capital is linked to a focus on production. There are some variations between companies and sectors as to the importance of different barriers (Palm and Thollander 2010), policies aimed at overcoming these barriers may therefore be more successful if targeted at specific areas of industry.

As the characteristics of a subsector are important in determining the drivers and barriers to energy efficiency so are the characteristics of a particular technology. De Beer (2000) uses the following system in defining the degree of technical change associated with energy efficient technology. Examples are offered from the cement sector, which is further discussed in Chapter 7:

- **Evolutionary change:** this requires no significant change in the process or the output. The change would normally account for a small improvement and would involve retrofitting an additional technology to a plant (with minimal disruption) or replacing a piece of equipment with a direct substitute. For example, replacing a motor with a higher efficiency unit that performs an identical service, or in cement manufacture the addition of an extra stage of preheating to the kiln.
- **Major change:** this will normally involve a change in the nature of the product and/or the processes being undertaken. This may involve major changes in the plant but would not require a whole new plant. This would usually be accompanied by significant changes in energy use. An example of a major change from the cement industry would be the switch from a wet to a dry process.
- **Radical change:** this would normally require a new plant, but may represent a leap forward in terms of performance. The product itself may change, whilst still performing the same energy service. An example of a radical change in the cement industry would be a change from Portland cement production to an alternative magnesium based cement.

Barriers such as risk and the disruption of production obviously increase as the technology becomes more radical. However the drivers to energy efficiency can also be increased by undertaking more radical options. The discussion here mostly applies to evolutionary changes, the majority of the improvement potentials explored in the current work are also evolutionary changes.

4.1.2.1 The rebound effect

The rebound effect is not classed as a traditional barrier to realising energy efficiency. It may limit the effect that energy efficiency savings have however and so a brief discussion on the matter is included here. The rebound effect is the mechanism through which improvements in efficiency do not lead to the full savings potential being realised. The effect can be either direct or indirect (Sorrell 2009). An example of a direct rebound effect in the manufacturing sector would be that improved efficiency (and hence lower energy costs) encourage the substitution of energy for labour, or other inputs, in production (Greening et al. 2000). An indirect effect example is that the cost savings from efficiency gains may be reinvested in additional equipment, which itself will have an energy requirement to produce (Sorrell 2009). Indirect effects can also take place outside of the manufacturing sector (Sorrell 2009). It is difficult to quantify the rebound effect in manufacturing (Greening et al. 2000), partly due to complex inter-sector linkages. There may also be macroeconomic effects caused by increased efficiency reducing global energy prices (Gillingham et al. 2013). Although some rebound does exist it is very unlikely to cause 'backfire', that is a net increase in energy demand due to improved efficiency (Gillingham et al. 2013), and so should not discourage efficiency improvements being made.

4.2 UK POLICY, EFFECTIVENESS AND FUTURE DIRECTION

Policy, if used effectively, can increase drivers and reduce barriers to energy efficiency. This section looks at the types of policy available and briefly examines the current policies influencing energy efficiency in UK industry. The field of energy policies, and proposals, is seemingly vast, and often confusing. The current section aims to cover the most important policies that influence energy use and emissions in UK industry, and to examine their influence on the drivers and barriers to increasing energy efficiency. Appendix 5 gives a more complete description of the various policies referred to here.

Policy is most effective when it influences the most significant drivers and barriers. There is an economic cost associated with the use of policies, either to the government, the company, or both. Policies, in addition to being effective, therefore also need to be efficient in the costs of achieving the reductions (The Economist 2009). If policies are not effective sufficient cuts will not be made, if they are not efficient the costs of averting climate change, estimated at around 1% of global GDP per year (Stern 2007), will mount, making it harder to make the required emission cuts. Policy instruments available can be grouped into the following headings:

- **Cap-and-trade:** a cap is set on the total amount of emissions and this total is allocated between all emitters involved in the scheme. If a company exceeds its allocation it must purchase additional allowances, if a company emits less than its allocation it can sell allowances. Cap-and-trade relies on providing a suitable number of allowances to set the price at the correct level, which can be difficult. Unlike a carbon tax (see below), it does set an overall cap on emissions. The EU Emissions Trading System (EU ETS) and Carbon Reduction Commitment (CRC) are cap-and-trade schemes.
- **Carbon tax (or price):** provides a high level of control as the price of emitting carbon is set, and so gives a clear price signal to firms and allows future investments to be planned. A carbon tax is, in most cases, the preferred choice of economists (The Economist 2009). The Climate Change Levy (CCL) is a carbon tax applicable to UK industry. The associated Climate Change Agreements (CCAs) provide relief from this carbon tax if negotiated targets in terms of energy use or emissions are reached.
- **Subsidies and loans:** help establish technologies that are not currently marketable, they can help overcome the barrier of limited capital. This can be important in accelerating the development of low carbon technology. Subsidies also cost the taxpayer however (although loans may not beyond administration costs). The government has to make, sometimes difficult, choices over which technologies to support, in essence backing winners. Subsidies and loans include the Green Investment Bank (GIB), the Enhanced Capital Allowance scheme from the Carbon Trust, fiscal incentives relating to CHP, and the Renewable Heat Incentive (RHI).
- **Regulation:** sets standards for equipment efficiency or emission levels. This is important where the market is not working well and companies are still making

poor choices as regards energy use or carbon emissions. It can be very effective if targeted at the right areas. Regulation tends to be unpopular however, as it involves micromanaging the choices of businesses. This is an area where there is currently little policy in the UK and potential for savings exist, in the US and Canada regulation of industrial motors has been successful (IEA 2009).

- **Information:** as discussed above lack of information is one of the greatest barriers to increasing energy efficiency in manufacturing, policy can act to supply information to companies, overcoming this barrier. This approach has the advantage of not costing companies, therefore protecting against carbon leakage and damage to the economy if companies' costs are raised in relation to their international competitors. Information can be provided through a number of government funded organisations including the Carbon Trust and Environment Agency.

There are a number of UK government documents that set out the policies for the manufacturing industry, relating to emissions reduction and improved efficiency, and frame the approach towards the industrial sector within the economy wide approach (DECC 2012h, DEFRA 2007e, DTI 2007, HM Government 2006, 2009a, 2009b, 2011). In 2011 an EU Energy Efficiency Directive aimed at ensuring the target of a 20% reduction in EU primary energy use by 2020 is reached was published. In the UK this led to the founding of the DECC Energy Efficiency Deployment Office (EEDO), which has developed the government's energy efficiency strategy, published at the end of 2012 (DECC 2012g). A Call for Evidence to develop this strategy (DECC Energy Efficiency Deployment Office 2012) was responded to by the current author (as part of a team), drawing on aspects from the current work.

4.2.1 Effectiveness of current policy in influencing drivers and barriers

It is generally difficult to place a quantitative measure on the effectiveness of a policy. Separating the influence of a certain policy compared to a business-as-usual (BAU) situation is complicated, it has not stopped measures of this form being made however. These quantitative measures have been referenced where available in the discussion of policy in Appendix 5. The main focus of the discussion here will be on how the existing policies can affect the drivers and barriers to energy efficiency.

The effect of policy on the drivers identified is relatively simple. Cap-and-trade schemes, and carbon taxes, increase the financial incentives available through energy efficiency. Subsidies can improve the economics of a project and help overcome barriers. Regulation can be a strong driver and is an approach that is maybe underused in the UK. The drivers of indirect benefits and individual champions are maybe not easy to directly influence through policy. However the existence of policies can increase the information available about and the profile of energy efficiency (see the discussion on barriers below), which can increase the understanding of indirect benefits and the existence of individual champions.

Sorrell et al. (2011) found that a *'policy mix'* is required to overcome barriers to industrial energy efficiency due to the variation of barriers with different technologies and industries. Overcoming a single barrier is not effective if other significant barriers remain. The most significant barriers to energy efficiency measures were found to be focus on production, lack of information and hidden costs. Policy can demand that attention is given to energy efficiency issues, partly overcoming a focus on production. Overcoming hidden costs is somewhat more difficult but providing information so they can be understood, and properly accounted for, could have an effect. Lack of capital, sometimes identified as a significant barrier, is also targeted by policies providing subsidies and loans for energy efficient technology. Given the importance of information in helping to overcome a range of barriers and the often indirect nature of its effectiveness it is discussed below in greater detail.

Lack of information is an interesting area that policy can help overcome. It is highlighted by a number of studies as a key barrier to realising energy efficiency. Policy that is not specifically targeted at overcoming a lack of information can still be effective in doing so. Any scheme targeted at reducing energy use or emissions will require some effort from a company subject to the policy in order to comply and fulfil the administrative requirements associated with a scheme. Reporting current levels of emissions or energy use is required under the EU ETS, CCAs and CRC, this can increase a company's understanding of its energy use. This is an important first step in improving energy efficiency. A lack of data can lead to bad decisions regarding energy use, which can be very damaging long-term (Jollands et al. 2010). Lack of information regarding technology options within a company can be overcome by a policy's requirement to reduce emissions levels. As an example of this effect it was found that in general the CCA targets have easily been reached and in many cases surpassed (Ekins and Etheridge 2006). It has been suggested this is due to the effect that the negotiation process and setting of targets has had in raising awareness of the availability of cost effective emissions savings (Ekins and Etheridge 2006). In schemes that more directly target lack of information, material needs to be spread effectively for maximum impact. The perception of different information sources can vary significantly between different industries (Palm and Thollander 2010). Some companies trust consultants for energy efficiency information, others their trade association, and others government supplied information. Rohdin and Thollander (2006) found information needed to be *'specific, personal, vivid and simple'* to have the maximum chance of acceptance, they also found information from colleagues and consultants was seen as more creditable than that from seminars, conferences, suppliers, and journals (these findings were in relation to the non-energy-intensive sub-sector of manufacturing). This may be as, in many cases, the information from colleagues and consultants involves technologies that are commercialised and proven in other applications, whereas the other information sources often involve technologies that are seen as more risky. Jollands et al. (2010) found information needs to be both credible and relevant to the audience. DeCanio (1993) suggests that the government can act effectively as a trusted *'clearing house for information'* and can also help reduce the perceived risk of projects by publicising results of the successful deployment of efficient technology. However De Groot et al. (2001) found for technological information most firms preferred to rely on specialist publications rather than formal government organisations and therefore government would do well to use these existing intermediaries. What can be drawn from these rather conflicting ideas on the best way to disseminate information is that, like many aspects of industrial energy efficiency, there is variability between subsectors and companies regarding the optimal approach. The individual's personal viewpoint and past experience is likely to determine which source of information is most trusted, and so most effective. It is therefore important to try to cover as many bases as possible, supplying information through a variety of sources, both general and specialist, to different subsectors of manufacturing.

4.2.2 Future direction of policy

The targets imposed by current energy efficiency schemes appear to have, on the whole, been easily reached (see Appendix 5), which has led to criticisms. This could partly be expected when schemes are in the early stages and governments tend towards leniency in targets until it is clear the effect a certain policy may have, in order to avoid placing heavy economic burdens on affected companies. Based on the early stages of current schemes there are proposals to tighten them for subsequent phases (as discussed in Appendix 5). The awareness effect coming out of even easily reached targets has been shown to be important. This section will not examine specific future policies but rather discuss the improvements that would likely be effective, based on lessons from current policy.

4.2.2.1 Simplification and long term targets

One feature of the current set of policies is that they can be overlapping. The EU ETS, CRC, CCL and from 2013 the Carbon Floor Price (CFP) can all affect the price of emitting carbon (directly and through purchasing electricity). It is the view of industry that a single, clear scheme aimed at reducing carbon would be preferred (EEF 2011b). There have been proposals to simplify the CCAs and reduce overlap with the EU ETS and CRC (DECC 2011a). Policies also have the potential to add barriers to realising energy efficiency if they become too complex, especially when multiple policies exist, taking up too much staff time with the administrative burden involved (EEF 2011a). Another aspect of policy that is linked to simplification of the current policies is a clear long-term strategy so companies can plan accordingly with investment decisions. If the government is not clear about the long-term plans for policies it can also increase the perceived risk of projects that rely on such policies to offset costs.

4.2.2.2 Importance of RD&D

Long-term clarity of policy is important for company decision making, as discussed above. A long-term approach to policy is also required to ensure that the ultimate targets for carbon reduction are reached, and not sacrificed by short-termism. Longer term options for the decarbonisation of UK industry include electrification of processes (in tandem with low carbon electricity generation), the use of biomass (including biogas for higher temperature applications) and CCS (DECC 2012h). For these to develop as viable future options early efforts in terms of innovation and development are required. The view of industry is that investments in RD&D with a long-term view to reducing carbon emissions are not currently rewarded by policy (EEF 2011b).

An example of successful R&D strategy can be gleaned by looking at historical schemes. The current author has been involved, as a co-author, in a publication undertaking an 'Impact review of past UK public industrial energy efficiency RD&D programmes' (Griffin et al. 2012), which is reproduced in Appendix 6. The Energy Efficiency Demonstration Scheme (EEDS), which ran from 1978-1989 was the main scheme in the only period of significant sustained public investment in industrial energy efficiency RD&D in the UK (see Fig. 4-2). Support was given to the applied RD&D of projects for innovative technologies, with perceived demonstration value, and existing technologies used in novel industrial settings. This support was given using shared cost contracts. This RD&D support then fed into a pool of technologies available for demonstration projects for which host firms could receive a grant of up to 25% of the capital cost. The host company in return allowed the project to be independently monitored, and for the results and lessons to be disseminated through industry. By the end of the scheme the EEDS had achieved a cost-effective ratio (the ratio of savings to in energy bills to government spend) of 8.5 (which becomes 11.5 if adjusted for 2010 industrial fuel prices) (Griffin et al. 2012). The annual emissions saving at the end of the scheme was approximately 18MtCO_2, at a cost of £3/tCO_2 (this becomes 15MtCO_2 and £6/tCO_2 using 2010 prices, emission factors and industrial fuel mix) (Griffin et al. 2012). It was estimated that the scheme lead to increased savings in industrial energy demand of 18-30%, above what would be seen in the absence of the EEDS (the 'additionality' of the scheme) (Griffin et al. 2012). The general perception of the EEDS was that it benefited from the objectivity of information and management and the close engagement of industry, the scheme provides a well-audited case study for industrial energy RD&D and could by an important reference if a similar scheme was adopted today.

4.2.2.3 A holistic approach

Policy has the potential to influence not just the energy and carbon emissions involved in the manufacture of a product, but those throughout its lifecycle. This includes the emissions before the manufacturing process (eg. extraction of raw materials), during the use-phase of the product's life, and during its disposal and recycling (or preferably reuse). For some products these indirect emissions can be greater than those associated with the manufacturing process. For more on this important area see, for example Hammond and Jones (2008) and Hammond and Jones (2011). Policy that rewards efforts to improve lifecycle emissions, even if they increase emissions during manufacturing are favoured by manufacturers' (EEF 2011b). It is recognised that such policy would be difficult to implement, and has scope for being done badly (EEF 2011b). There have been some steps in this direction in relation to EU legislation on the recycling of waste electrical and electronic equipment (Environment Agency 2012). The UK and Europe could learn from the success of Japan's Home Appliance Recycling Law (HARL) system. HARL is an effective strategy in incentivising Design for Recycling as it ensures the equipment manufacturer is accountable for its own products at end-of-life. This is also known as Individual Producer Responsibility (DTI 2005b).

4.2.2.4 Carbon leakage strategy

Another area of policy that needs addressing with a clear strategy is the question of carbon leakage. There is concern that a high carbon price, if only applied to the UK (or EU) could result in a higher proportion of energy-intensive manufacturing moving outside the UK. This would obviously hurt the economy of the affected regions, carbon leakage could also lead to higher overall emissions due to manufacturing in the EU tending to be more efficient than in other nations, and additional emissions from transport requirements, if products are imported back to the EU. A report by the Carbon Trust on the subject of carbon leakage due to the EU ETS (Carbon Trust 2008), found 90% of UK manufacturing activities would be unaffected by paying for all their allowances within the EU ETS (many allowances are currently given for free). Sectors most in danger of carbon leakage are Lime, Cement, Iron and Steel (via. blast furnaces) and Aluminium (Carbon Trust 2010e). There have been further studies into this somewhat contentious area (Carbon Trust 2008, 2010e, Clo 2010, McKinsey & Company and Ecofys 2006). A survey by EEF (2011c) of 76 senior manufacturing executives did find that from 2009 to 2011 the proportion of companies taking action to reduce their carbon emissions had risen from 54% to 84%. However coupled with this 75% of companies thought the costs of climate and environmental policies had increased over the same period and were damaging competitiveness. There has been support for energy-intensive industries from the government. Beginning in 2013 a £250 million fund will assist electrically intense industries in meeting costs from the EU ETS and CFP, and also increase the level of relief offered on the CCL by participating in a CCA (DECC 2012h). A call for evidence has been put out by the government to assess where compensation should be given (BIS 2012a). Balancing the possibility of carbon leakage with the need to reduce emissions from industry is a difficult task.

4.2.2.5 International agreements

One solution to protect against carbon leakage is the existence of an international carbon tax, emission trading scheme, or similar mechanism. Climate change is a worldwide problem, with no link between where carbon is emitted and where the effects are felt. It is not just the UK, but the world, that needs to take action to limit emissions that contribute to climate change. That threat of carbon leakage means that without a worldwide agreement the UK industrial policies may not decrease worldwide emissions. The UK already imports a significant amount of the products consumed nationally, this is primarily the result of different costs for labour, energy, taxes etc., rather than a carbon price currently. An alternative to examining the direct emissions of a country is to measure the emissions associated with the consumption of goods and services in a country, therefore taking account of imports and exports. It was estimated by Davis and Caldeira (2010) using a consumption based approach to emissions accounting that in 2004 the UK imported more than 30% of its emissions. An international agreement would therefore have a direct and an indirect effect on UK emissions. It is very difficult to reach any worldwide agreement on emissions reduction however, as has been shown by previous international negotiations. A full international agreement is not expected for a number of years. As an interim step global carbon intensity sector agreements and targets have been proposed (EEF 2011b), it is expected that these would still be difficult to set up however. International technological standards are also important in terms of pushing efficiency forward (DECC 2012h).

4.2.2.6 Non-energy-intensive subsector

Current policy focuses on the energy-intensive subsector. There have been moves with the CRC to include large energy users within the non-energy-intensive subsector in policy. This still neglects smaller businesses, where barriers are often accentuated further, with more limited resources to commit to improving energy efficiency (Cagno et al. 2010). These smaller, less energy-intensive businesses, not covered by binding policy levers, may account for up to 45% of the total emissions reduction potential from non-residential buildings and industry (Committee on Climate Change 2008). The non-intensive subsector can often offer relatively greater savings potential than the energy-intensive industries (Metz et al. 2001). The IEA recognises the need to address SMEs in future energy policy (Jollands et al. 2010).

The next section of the current chapter proposes a method for splitting industry into an energy-intensive subsector, with strong drivers (including policy) to improving energy efficiency, and a non-energy-intensive subsector, with weaker drivers for improving energy efficiency. This split can then be used to examine the difference between these subsectors and the effect that the relative strength of drivers may have.

4.3 THE ENERGY-INTENSIVE AND NON-ENERGY-INTENSIVE SUBSECTOR

Due to the large variability seen in the way energy is used in manufacturing the drivers to energy efficiency can vary significantly throughout the sector. The current section aims to split the manufacturing sector into an energy-intensive (EI) and a non-energy-intensive (NEI) subsector. The split into subsectors was designed so that EI subsector has stronger drivers for increasing energy efficiency. The split is based on drivers rather than barriers as the drivers to energy efficiency are more strongly based on the characteristics of a subsector than the barriers, which are often associated more with the characteristics of an individual site. The split into an EI and NEI subsector is made so the effect of drivers to energy efficiency can be better understood by analysing the differences seen when examining energy use in the EI and NEI subsectors separately.

Although 'energy-intensive' industry is often referred to there is not a widely used definition of the term. Ramirez et al. (2005) provide a review of methods previously used to split the industrial sector into an energy-intensive (EI) and non-energy-intensive (NEI) subsector. This was based on a survey of sixty energy demand studies of the manufacturing sector. Three broad approaches were distinguished:

1. Single out a few major EI sectors and treat the remainder as a residual group.
2. Establish a limit that differentiates EI from NEI sectors.
3. Define the intensiveness of a sector via its process characteristics or other 'known' definitions.

The second approach is adopted here with the limits that differentiate the EI and NEI subsectors based on quantitative analysis of factors that are thought to affect the drivers to energy efficiency of a subsector. The current section provides details of the split into the EI and NEI subsector, some basic analysis once the split is made is also undertaken. A subsequent chapter performs a decomposition analysis of the EI and NEI subsector separately to examine the performance of each subsector and the causes of changes in energy demand (see Chapter 5). The work presented here and subsequent decomposition analysis of the separate subsectors is partly inspired by the work of Ramirez et al. (2005).

4.3.1 Methodology

The criteria utilised in establishing a limit between the EI and NEI subsectors were chosen based on the drivers for increasing energy efficiency in industry. From section 4.1.1 these drivers are financial savings, legislation, indirect benefits and individual champions. The presence of individual champions is considered very company dependent and cannot be analysed at a subsectoral level. Three criteria were chosen to assess the strength of the remaining drivers, they were:

1. The energy intensity (energy use per unit of output) of a subsector.
2. The proportion of total financial costs represented by energy for a subsector.

3. The mean energy use per site in a subsector.

The first and second criteria for defining the EI and NEI subsectors are a representation of the direct and indirect financial incentives to energy efficiency. The first criterion is fundamental to the definition of a subsector as energy-intensive or non-energy-intensive. Where legislation targets subsectors considered 'intensive' (for example the EU ETS and CCAs above) it is not always clear how this definition of 'intensive' subsectors is made. It is thought to at least be partly based on this measure of energy intensity, as in the first criterion, however. The second criterion is heavily related to the potential for financial savings through energy saving measures. The third criterion is related to financial savings available and legislation. Although the proportion of costs represented by energy may be low at a site, if it is a large enough site in terms of its total energy use it may still make financial sense to employ an energy manager and actively seek saving options. Legislation is also often based on a site's energy use, irrespective of its output (as in the case of the EU ETS and CRC). To be classified as EI a subsector needs to have any one of the above criteria greater than a chosen limit (defined below). A high value for any of the criteria should represent a strong driver for energy efficiency. Ramirez et al. (2005) adopted a similar approach to that here in defining subsectors as EI or NEI, using the first two criteria above in their study of the Netherlands. The current work therefore builds on this for the UK, and adds the third criterion to the analysis.

4.3.1.1 Data used

In undertaking the analysis here energy was measured in primary terms and output in value of production at constant prices. The datasets for these measures were Energy Consumption in the United Kingdom (ECUK), the index of production (IoP), and the Annual Business Inquiry (ABI), details on these sources and reasons for their use are examined in Chapter 2. Information on energy costs and total costs were extracted from the Annual Business Inquiry (Office of National Statistics 2009a). Energy costs were grouped with water costs in the ABI, which although not an ideal measure should give a fair approximation of the significance of energy costs to the business. Schemes to save water and energy are often considered in tandem by a company. The number of sites (or enterprises[14]) in each subsector of industry were also taken from the ABI.

The analysis was undertaken at the highest disaggregation level available, this was limited by the Index of Production data. Seventy two sub-sectors of industry were represented, these are detailed in Appendix 3. A lower level of disaggregation was also used due to limitations in the time period for which data was available at a higher level of disaggregation. This was at the 2 digit SIC level (which gave twenty two sub-sectors

[14] In the Annual Business Inquiry (ABI) an enterprise is defined as: '*the smallest combination of legal units, which have a certain degree of autonomy within an enterprise group. An enterprise group is simply a number of enterprises under common ownership'*. The number of enterprises is therefore a good measure of the number of sites in a subsector for the purpose of the current work.

of industry). Only using the higher level of disaggregation would have limited the further analysis that could be undertaken using the split into the EI and NEI subsectors.

All the results shown here are the mean for 2002 to 2006 with the largest and smallest values removed. This time period was the most recent five year period, at the time of undertaking the work, for which all data was available. The highest and lowest values were removed when constructing the mean values as at a high level of disaggregation there were concerns over inaccurate and missing data in some of the sources used (see Chapter 2 for details). Some subsectors did not have all the information available to perform analysis at high levels of disaggregation and so were excluded from the analysis, these are all small users of energy and were classified as NEI.

4.3.2 Defining the split criteria

Deciding on the value of each criterion that determines the split between the EI and NEI subsectors is difficult, and somewhat arbitrary. To assist in defining the limit for the split the chosen criteria were plotted for each of the subsectors analysed in Fig. 4-3, Fig. 4-4 and Fig. 4-5. In the plots the dotted line represents the value of the criterion when the manufacturing sector as a whole is analysed, the dashed line represents 150% of this value. Note that these plots all use log scales, indicating the large range of values seen in the criteria throughout the manufacturing sector. It is expected that for each of the criteria used to determine the split between the EI and NEI subsector that the majority of subsectors would be clustered around a lower set of values, with a small number of subsectors showing significantly greater values, this was found in work by Ramirez et al. (2005). These subsectors with significantly higher values of the criteria would then be classified as EI. This is the pattern seen in Fig. 4-3 and Fig. 4-4 where the majority of subsectors are below the dashed line (indicating one and a half times the result for the whole manufacturing sector). This value of 150% of the sector result was therefore taken as the value for the split between the EI and NEI subsectors. It can also be seen that the subsectors with the highest overall energy demand (indicated by diagonal lines) tend to be the EI subsectors. Fig. 4-3 shows that there is a subsector with very low energy intensity in comparison to other subsectors. This is the tobacco subsector (SIC code 16). There is concern over the accuracy of the data available for this subsector and so it is removed from the results shown from here on, it is classified as NEI.

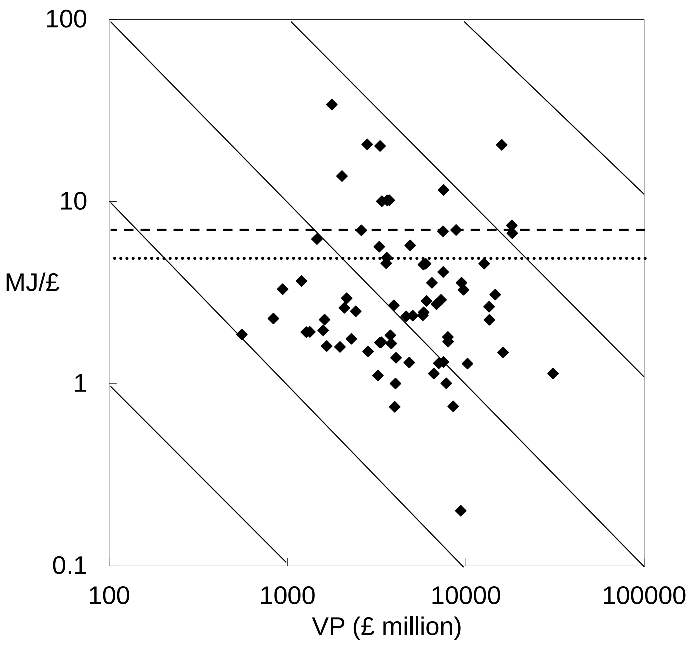

Fig. 4-3: Energy intensity against value of production (VP) for subsectors of manufacturing, 2002-2006. Diagonal lines indicate constant energy demand.

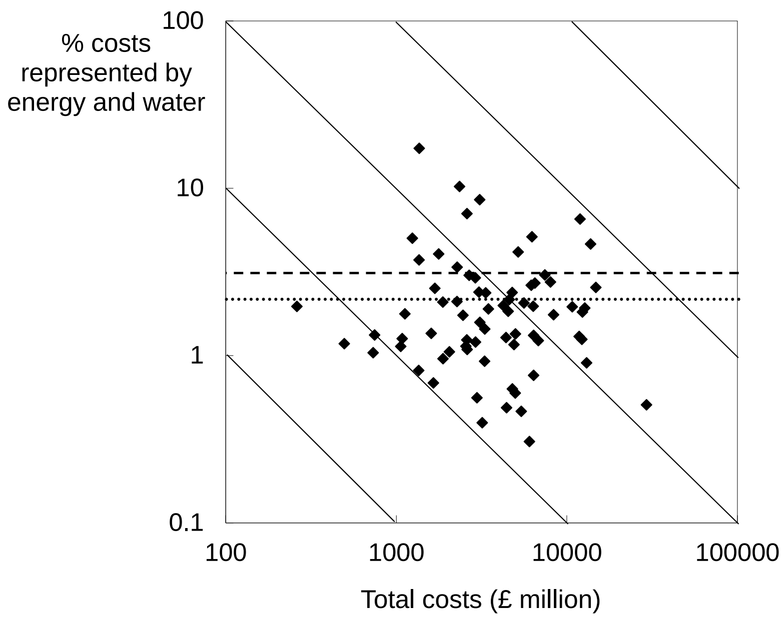

Fig. 4-4: Percentage of total costs represented by energy and water costs against total costs for subsectors of manufacturing, 2002-2006. Diagonal lines indicate constant total energy cost.

Fig. 4-5 showing the energy demand per enterprise does not display the same spread of results as the previous plots. Here the spread is relatively greater and less clustered around lower values. For this reason an alternative criteria for determining the split between the EI and NEI subsectors was used. As certain policies target large users of energy these were used as a guide for determining a sensible level for the value of the split. The criterion for inclusion in the CRC appears to be a sensible basis as it is designed to target large users of energy who are not covered by the EU ETS. For inclusion in the CRC a site must have an electricity usage of 6000MWh/yr. this is 21.6TJ/yr or 56.2TJ/yr as a primary equivalent (using the appropriate electricity primary conversion factor, see Chapter 2). Fig. 4-6 shows the proportion of total energy use represented by different fuels at the 2 digit SIC level. The CRC is aimed at large users of energy, not involved in the EU ETS or CCAs, and so covers those subsectors with proportions of electricity use from approximately 50% (for the textile sector, SIC 17), to 80% (for the electronics sector SIC 30-33) therefore electricity demand required for inclusion in the CRC could cover total site energy use of 62-100J/yr. The upper limit of 100TJ/enterprise is adopted, it gives a sensible split in the number of subsectors included in the EI and NEI subsector, similar to that from the other criteria. This 100TJ/yr limit is indicated by the dot-dash line in Fig. 4-5.

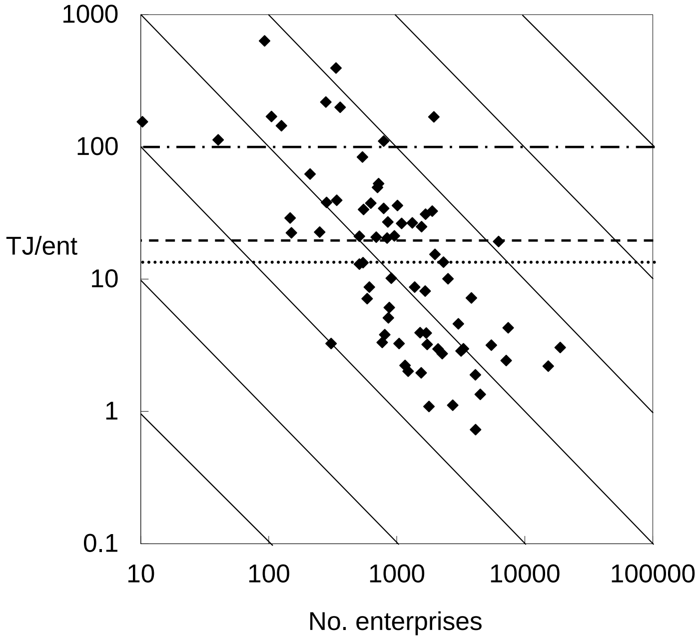

Fig. 4-5: Mean energy demand per enterprise against number of enterprises for subsectors of manufacturing, 2002-2006. Diagonal lines indicate constant energy demand. Dot-dash line indicates 100TJ/ent.

As previously mentioned the choice of values for the split is somewhat arbitrary and these values were adopted not only for the reasons above, but also as they were found to give sensible results, using knowledge of the manufacturing sector as guidance. Different aggregation levels for the split into the EI and NEI subsectors used the same criteria. In summary to be classed as EI, with higher drivers to energy efficiency a subsector needs to have a mean value above any of the three criteria:

- An energy intensity of 6.46MJ^P/£VP
- Energy and water costs of 3.3% of total costs
- Energy use of 100TJ/enterprise

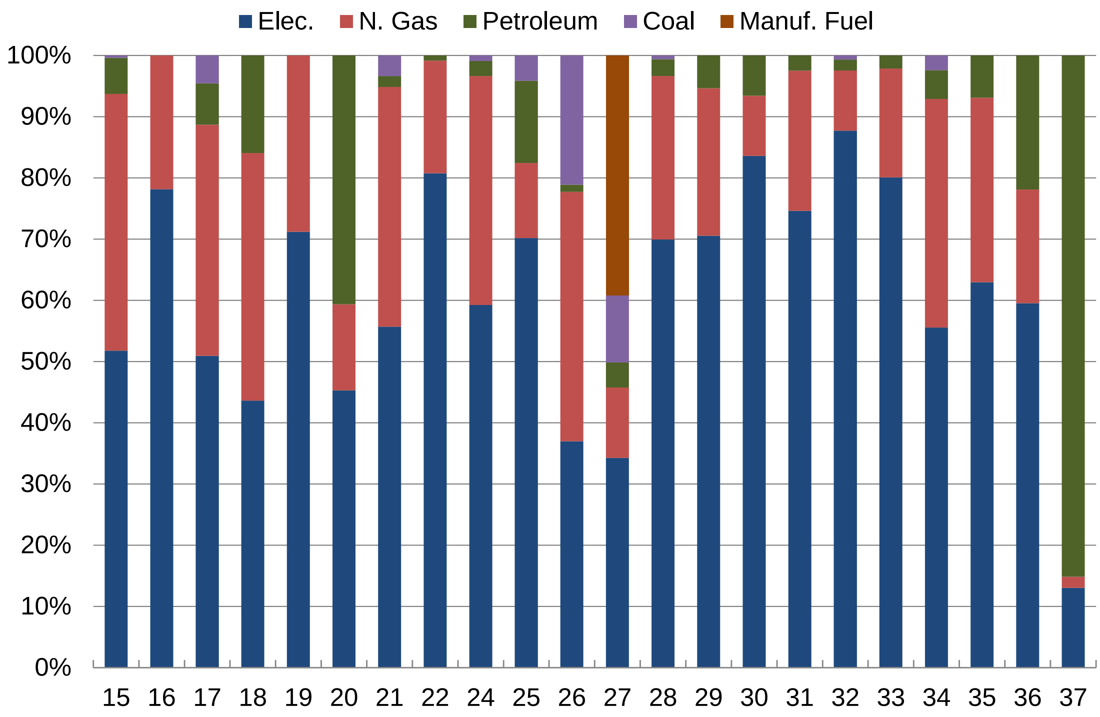

Fig. 4-6: Fuel use by 2 digit SIC level, primary energy terms, 2008. Adapted from DECC (2010c).

4.3.3 Results

Results for the split into an EI and a NEI subsectors are shown in Fig. 4-7, for the highest level of disaggregation possible with the datasets. Energy intensity and proportion of total costs represented by energy costs are represented by the position of the points. The area of the data point represents energy use per enterprise. Dashed lines show the limits between the EI and NEI subsectors. The subsectors that exist in the non-intensive portion of Fig. 4-7, but have an energy demand per enterprise that classes them in the EI subsector, are shaded.

The subsectors that are classed as EI at this level of disaggregation are:

- 15.4: Manufacture of oils and fats
- 15.6: Manufacture of grain mill products and starch
- 15.91,2,7: Manufacture of distilled alcoholic drinks and malt
- 17.1-3: Manufacture of textile fibres, weaving and finishing of textiles
- 20: Manufacture of wood and wood products
- 21: Manufacture of pulp, paper and paper products*
- 24.1: Manufacture of basic chemicals*
- 24.2: Manufacture of pesticides and other agro-chemical products
- 25: Manufacture of rubber and plastic products*
- 26: Manufacture of other non-metallic mineral products*
- 27: Manufacture of basic metals and fabricated metal products
- 29.4: Manufacture of machine tools
- 36.6: Miscellaneous manufacturing n.e.c.
- 37: Recycling

* indicates the analysis was performed at a higher level of disaggregation than the sector listed here but subsectors have been grouped when reporting for conciseness.

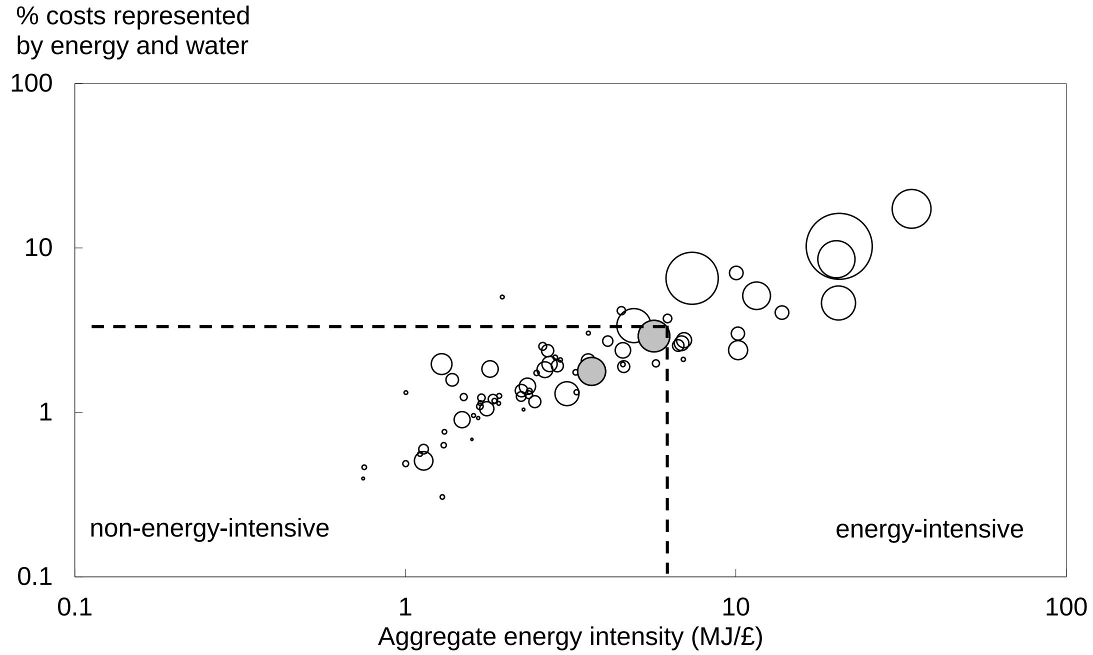

Fig. 4-7: Energy intensity, energy costs as a percentage of total costs and energy use per enterprise, 2002-2006 high level disaggregation. Area of points represents the energy use per enterprise.

Fig. 4-8 shows the same information as Fig. 4-7 but for a higher aggregation level, the 2 digit SIC level. Subsectors labelled are classed as EI, with the remainder being NEI. Note that the axes do not have log scales as in Fig. 4-7, the overall spread of results is lower at this level of disaggregation (as would be expected).

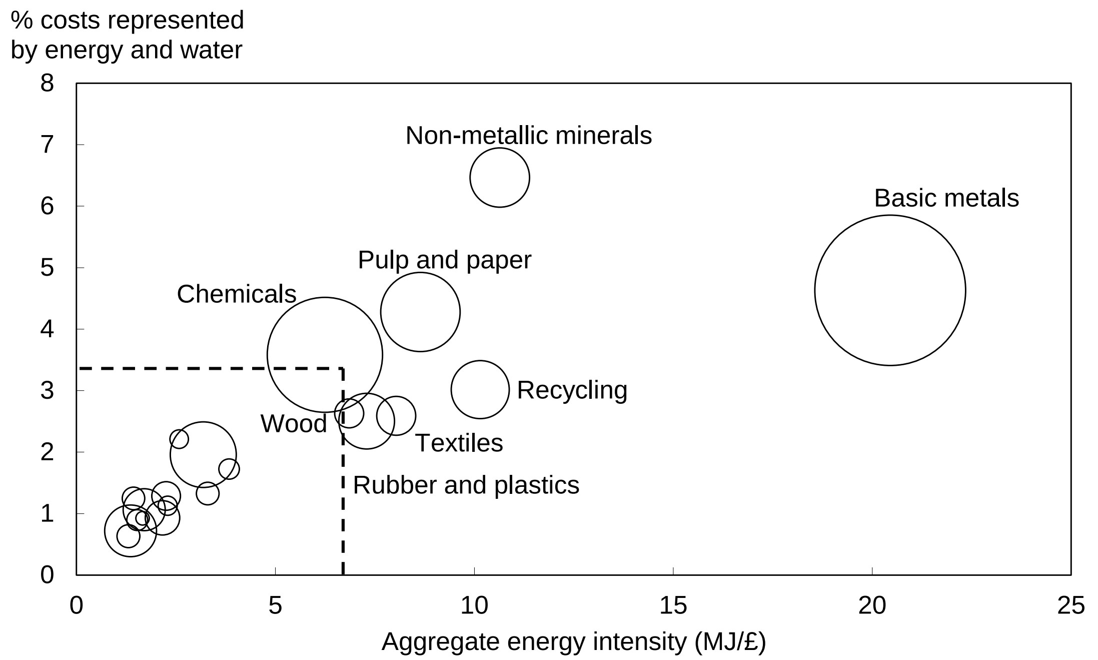

Fig. 4-8: Energy intensity, energy costs as a percentage of total costs and energy use per enterprise, 2002-2006 lower level disaggregation. Area of points represents the energy use per enterprise.

If the results utilising the lower level of disaggregation are to be used for further analysis it should be checked how closely they follow those at a higher level of disaggregation, and so how well they represent the split into an EI and NEI subsector. With the higher level of disaggregation 62% of energy demand is accounted for by the EI subsector, with a lower level of disaggregation this becomes 65%. Value of production in the EI subsector for the higher and lower level of disaggregation are respectively 28% and 34% of the total for the manufacturing sector. The effect on energy intensities, using the higher and lower level of disaggregation, are shown in Fig. 4-9. Energy intensity for the whole manufacturing sector is obviously unaffected by the level of disaggregation. The energy intensity of the NEI subsector is affected very slightly, being less than 3% over the period 2001-2007, and so is imperceptible in Fig. 4-9. The most significant difference using the different levels of disaggregation is in the EI subsector. A higher energy intensity at the higher level of disaggregation indicates that the lower level of disaggregation includes subsectors of manufacturing that should be classed as NEI, this is likely caused by the Chemicals subsector. This subsector is heterogeneous in its product outputs and at the higher level of disaggregation includes a number of subsectors classed as both EI and NEI, at the lower level of disaggregation the Chemicals sector is classed entirely as EI. Despite these shortcomings at the lower level of disaggregation it is still felt to provide a sufficient basis for the split to EI and NEI subsectors, and is used for further analysis when required.

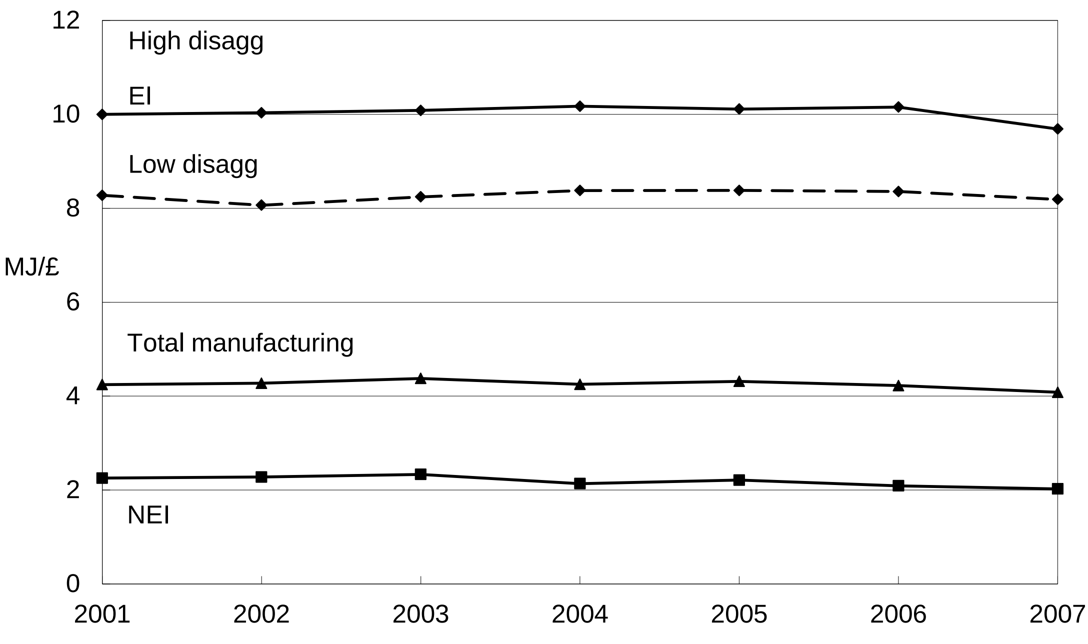

Fig. 4-9: Energy intensity of the EI and NEI subsectors under different levels of disaggregation, 2001-2007.

Fig. 4-10 and Fig. 4-11 show final energy demand by end use for the EI and NEI subsectors, in comparison to the whole manufacturing sector. Proportions of each subsectors' total demand are shown in Fig. 4-10 and the absolute demand is shown in Fig. 4-11. This split is based on the more aggregated subsector split due to the constraints of the data used.

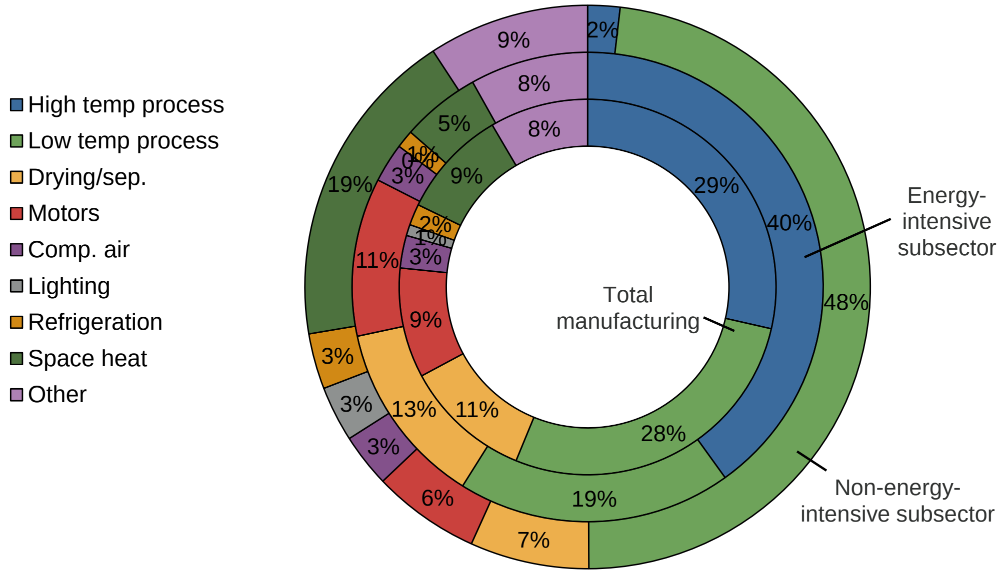

Fig. 4-10: Relative end use of energy in the manufacturing sector, energy-intensive subsector and non-energy-intensive subsector. Energy is in terms of final demand for 2008 (DECC 2010c).

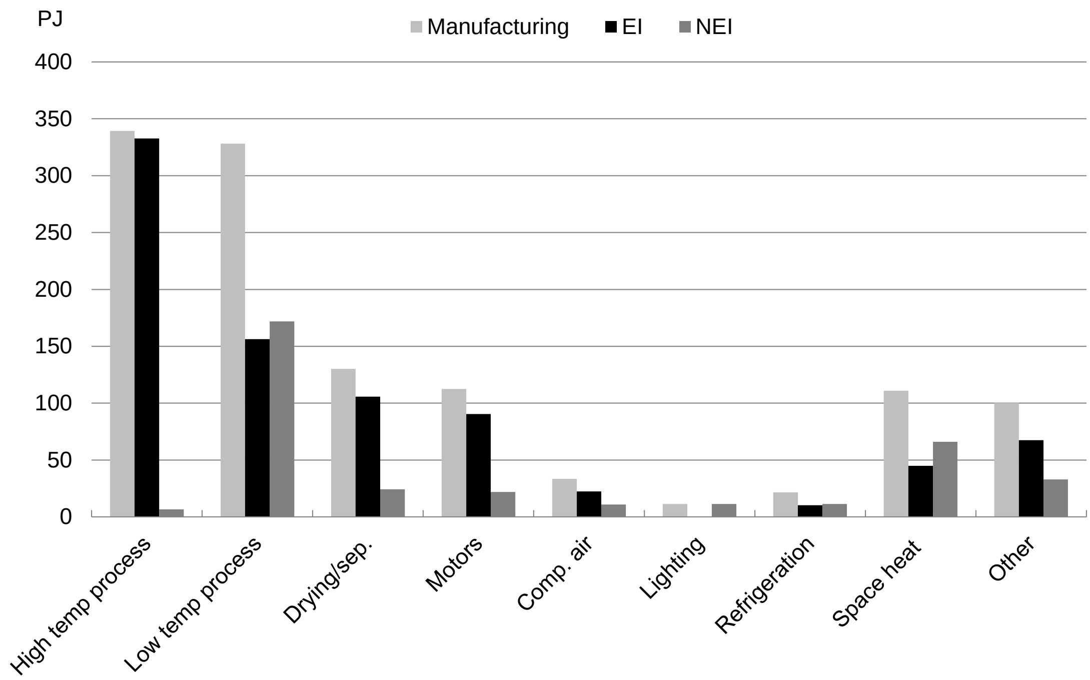

Fig. 4-11: Ends use of energy in the manufacturing sector, energy-intensive subsector and non-energy-intensive subsector. Energy is in terms of final demand for 2008. (DECC 2010c).

The main findings in terms of end use of energy between the subsectors are:

- Almost all high temperature processes (over approximately 300°C) are within the EI subsector.

- There is relatively greater low temperature heat demand in the NEI subsector (with similar absolute demand). Space heating is also greater in the NEI subsector.
- In relation to all heat demand (at any temperature, including drying and separation and space heating) there is similar relative demand between the two subsectors, with greater absolute demand in the EI subsector.
- Higher demand for motor systems, both relatively and absolutely in the EI subsector.

4.3.4 Discussion

There are recognised limitations to the top-down method adopted in defining the EI and NEI subsectors. It should be mentioned that statistical limitations such as the SIC system and restricted disaggregation affect the method utilised here, this is discussed more fully in Chapter 2, being characteristic of many such studies. The limits of disaggregation mean that there may still be significant differences in the drivers within a subsector as defined here. Even in a well-defined homogeneous sector the size of site, and other factors, can vary significantly and therefore affect the drivers to energy efficiency. It is felt that the split into the EI and NEI subsector, as defined here, still forms a useful basis for further analysis however.

The majority of policy aimed at improving energy efficiency focuses on the EI subsector. Similarly most technical studies on energy efficiency also focus on the EI subsector there are good reasons for this.

- A small number of EI subsectors comprise a large proportion of industrial energy demand. Therefore a small number of focussed studies into these subsectors can cover a significant proportion of total industrial energy demand.
- EI subsectors are more likely to apply energy efficiency measures due to the greater drivers in this subsector. Technical potential for improvement is therefore more likely to be realised.
- EI subsectors tend to make homogeneous products, meaning that the process routes are relatively few. Energy use is often dominated by a single (or small number) of intensive processes. This makes modelling energy use in the subsector, and finding technical improvements, an easier proposition.
- There tends to be better information on energy use in EI subsectors, and on technical improvements. This facilitates analysis into these subsectors.

Despite the focus of previous studies on the EI subsector (or perhaps because of this) there is thought to be considerable improvement potential within the NEI subsector (see section 4.2.2.6). As a lower number of studies have focussed on the NEI area there is also a knowledge gap that can be filled by examining these subsectors. The energy efficiency potential within the NEI subsector may be difficult to realise, given the decreased drivers to energy efficiency. In a study of Dutch industry Ramirez et al. (2005) found that over the period 1988-1999 the NEI subsector increased its decomposed energy intensity, indicating a worsening efficiency. This is obviously a concerning situation (the study did not examine the EI subsector to compare the performance over the same period).

Cross-cutting opportunities for energy saving have relevancy in both the EI and the NEI subsector. The NEI subsector is likely to have greater relative potential for such technologies. The subsector's product output, processes and energy use are more heterogeneous, process specific improvements therefore have limited impact. Analysis undertaken above indicates there are also opportunities for this cross-cutting approach within the EI subsector. The higher absolute energy use in the EI subsector means that once the energy-intensive, high temperature processes have been discarded the energy use between the subsectors is of similar magnitude. In the context of the work on cross-cutting opportunities in Chapter 3 the EI subsector is likely to have higher potential in saving energy from motor systems whilst the majority of relative potential for steam system improvement is within the NEI subsector. The increased use of CHP is available in both the EI and NEI subsector. The heat recovery potential is likely greater in the EI subsector. With high process temperatures waste heat will be at higher temperatures and this offers more options in how the waste heat can be utilised. Waste heat recovery is explored further in Chapter 6. Due to the increased drivers to energy efficiency in the EI subsector it may be that the energy saving opportunities, in all areas, are more likely to have already been realised than in the NEI subsector.

4.4 SUMMARY

The drivers and barriers to energy efficiency are important to understand. Even within a technical study, to have an appreciation of why a technology may be adopted, or otherwise, allows a greater appreciation of the situation. The drivers to energy efficiency are relatively straight forward, being due to financial saving opportunities, the need to fulfil legislation or the presence of a concerned person in a company. The barriers to energy efficiency are much more diverse with hidden costs, focus on production, lack of information and (in some cases) the availability of capital being found to be the main barriers.

Policy can act to increase drivers to adopting energy efficient technology or to remove the barriers. The field of policy, in relation to energy efficiency, is somewhat in its infancy with issues surrounding climate change and energy security being relatively recent (in their current guise). There is therefore considerable improvement available for energy policy in its effectiveness, coverage and simplification. This is not to say existing policy has not been effective to some degree. It has been found that even when policy is easy for companies to comply with, the awareness effect engendered can offer significant gains.

The non-energy-intensive sector of manufacturing is often ignored by energy policy and more generally by studies examining energy saving opportunities in industry. The energy-intensive subsector is generally easier to analyse but the non-energy-intensive subsector comprises a significant proportion of overall energy use, and it is thought that the potential for relative savings in this subsector may be greater than in the rest of industry. Here the industrial sector was split into an energy-intensive and non-energy-intensive subsector based on a quantitative analysis of criteria that were thought to affect the drivers to energy efficiency. The non-energy-intensive subsector, as defined, is responsible for 38% of the manufacturing sector's final energy demand. Cross-cutting technologies are likely to have greater relative impact in this subsector.

CHAPTER 5

DECOMPOSITION ANALYSIS

Energy-related carbon emissions from UK manufacturing fell, between 1990 and 2009, by approximately 3% per annum. This reduction could be caused by a number of effects that can act to increase or decrease the level of emissions. Decomposition analysis has been used in this chapter to separate the contributions of changes in output, industrial structure, energy intensity, fuel mix and electricity emission factor to the reduction in carbon emissions over this period. The chapter also examines differences in performance between the energy-intensive and non-energy-intensive subsector (as defined in Chapter 4). The underlying causes of the different effects that influence energy-related carbon emissions are examined. This work therefore both improves understanding of the trends seen in energy use and carbon emissions over the previous two decades and sheds light on how the energy-intensive nature or otherwise of subsectors and the drivers acting on improving energy efficiency have affected the reductions in emissions. This work was originally presented, in a less complete form (only examining the energy use of industry, rather than the carbon emissions emanating from this energy use) at the 23rd International Conference on Efficiency, Cost, Optimisation, Simulation and Environmental Impact of Energy Systems (ECOS 2010) in Lausanne, Switzerland from the 14th-17th June 2010. The paper was then selected in an extended form for publication in a special issue of Energy relating to the conference (Hammond and Norman 2012a), this extended paper is included in Appendix 6. In this chapter extra years were included in the analysis due to the greater availability of data at the time of writing.

5.1 BACKGROUND

As discussed earlier in this work, the manufacturing sector is difficult to analyse due to the large variability in the ways energy is used within the sector. Past trends in energy use and the resulting carbon emissions can help in better understanding the current situation and influence future decisions aimed at reducing energy-related carbon emissions. Fig. 5-1 shows energy related carbon emissions from manufacturing (SIC 15-37, excluding 23) from 1990-2010. A relatively constant fall in emissions has been seen over most of the period, with a more rapid recent fall caused by a recession. An examination of trends in energy demand within industry since 2000 is included in Chapter 3.

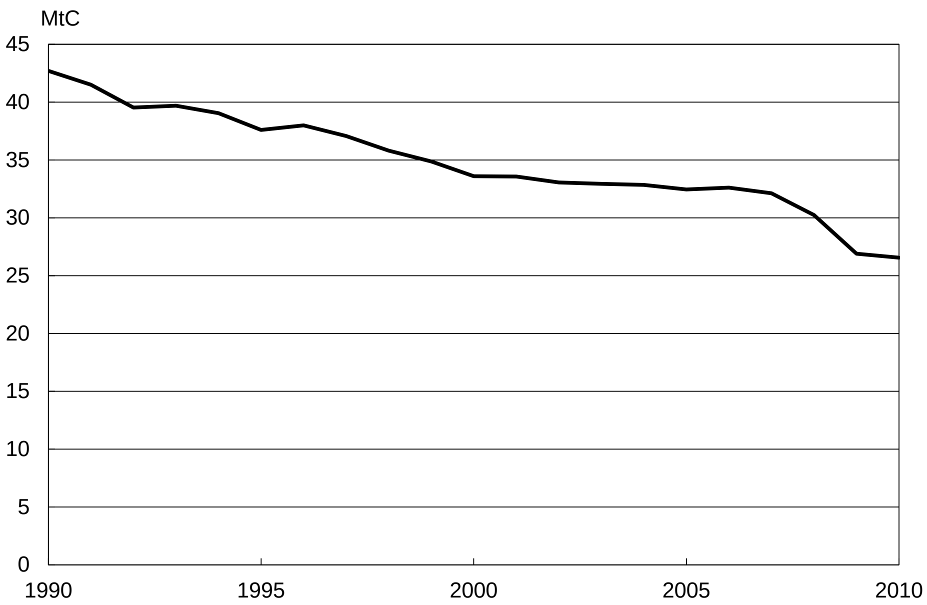

Fig. 5-1: Energy related carbon emissions from manufacturing 1990-2010, emissions are calculated based on final energy demand and fuel emissions factors.

Simply examining the changes in carbon emissions or energy use over time does not offer any insight into the reasons for these changes. Decomposition analysis (Ang and Zhang 2000) can split the changes in energy-related carbon emissions over time into a number of different factors. This gives a better understanding of the reasons for the changes observed. The contributing effects to a change in energy-related carbon emissions from the manufacturing sector are:

1. A change in **production**: if the sector output alters, manufacturing more or less product, this will almost always affect energy use.
2. A change in **structure**: over time the composition of the manufacturing sector may vary, and this can affect the energy use. For example, if the relative size of industries with a high energy intensity declines, the manufacturing sector may appear to be improving its efficiency, when in fact only a structural change has occurred.
3. A change in **energy intensity**: less energy is used to produce the same output.

4. A change in **fuel mix**: emissions factors (the carbon emitted for a given amount of delivered energy) vary by fuel, and so fuel switching can affect the emissions from energy use.
5. A change in **emission factors**: over time the emission factors of fuels and (especially) electricity can vary.

Previous studies have carried out decomposition analyses of energy use or energy-related emissions from UK manufacturing over the time period from the late 1960s to the mid-1990s (Department of Trade and Industry 1994a, Greening et al. 1998, Greening et al. 1997, Howarth et al. 1991, Jenne and Cattell 1983, Liaskas et al. 2000, Park et al. 1993, Schipper et al. 2001, Unander 2007, Unander et al. 1999), a review of worldwide Index Decomposition Analysis (IDA) studies up to the year 2000 is provided by Ang and Zhang (2000). The current work carried out a decomposition of the energy-related carbon emissions from UK manufacturing sector over the period 1990-2009, therefore updating these previous studies. The current work focuses on the UK, it therefore allows a higher level of sector disaggregation than many studies (although not being as broad as some of these previous studies, which compare the results of different countries). In addition, this work has decomposed the carbon emissions of the energy-intensive (EI) and non-energy-intensive (NEI) subsectors of manufacturing (as defined in Chapter 4) separately. It was anticipated that the EI subsector would exhibit stronger drivers for emissions reduction through improving energy intensity. The effects of production growth, energy prices, fuel mix and previous intensity improvements in determining changes in energy-related carbon emissions have been examined with reference to the results of the decomposition analysis.

5.2 METHODOLOGY

There are a number of methodological choices to be made when undertaking a decomposition analysis. They can potentially influence the results from the analysis, and so need to be made carefully, bearing in mind the aim of the study. It is important to be aware of the limitations arising from methodological differences when comparing the results of different studies. More generally, it should be remembered that no method will give a fully accurate representation of the changes seen. This is not to say that the results from such studies are not valid, but that they should be considered with knowledge of the limitations imposed by the technique and data availability. These limitations are discussed in reference to the methodology and results where applicable.

The broad technique of decomposition analysis utilised here is often known as Index Decomposition Analysis (IDA), and is based on statistical data. It was preferred to Structural Decomposition Analysis (SDA), which employs input-output tables. Although SDA analysis can give more refined decomposition of economic and technological effects (Zhao et al. 2010), IDA was used because of its simplicity, the availability of data, and as previous decomposition studies of the UK tend to use IDA (Department of Trade and Industry 1994a, Greening et al. 1998, Greening et al. 1997, Howarth et al. 1991, Jenne and Cattell 1983, Liaskas et al. 2000, Park et al. 1993, Schipper et al. 2001, Unander 2007, Unander et al. 1999). Its use thereby facilitates historical comparison.

The general IDA method assumes that *V* is the aggregate factor being examined and there are *n* factors affecting changes in *V* over time. These *n* factors are $x_1, x_2, \ldots, x_n$. The system under investigation is split into *i* sub-sectors. Over the time period *0* to *T* the aggregate factor changes from V^0 to V^T. This change with time can be represented as a ratio, such that the effects of different factors affecting the change in the aggregate factor (*V*) are multiplied:

$$D_{tot} = \frac{V^T}{V^0} = D_{x_1} D_{x_2} \ldots D_{x_n} D_{x_{rsd}} \tag{5-1}$$

Alternatively the change with time can be represented by a difference such that the effect of different factors are summed:

$$\Delta V_{tot} = V^T - V^0 = \Delta V_{x_1} + \Delta V_{x_2} + \ldots + \Delta V_{x_n} + \Delta V_{x_{rsd}} \tag{5-2}$$

For both this multiplicative and additive method there may be a residual factor (denoted by an *rsd* sub-script) representing change not accounted for by any of the *n* factors.

The choice whether to use a multiplicative or additive method is solely down to how the results of the study will be presented, for the current work it was chosen to use additive analysis as the results were felt to be more easily interpreted with this method.

There are a number of different variant techniques of IDA. A useful guide to the various options is given by Ang (2004). The log mean Divisia index method I (LMDI I) is used here, it was first introduced by Ang et al. (1998). The method is perfect in decomposition, having no residual term. It is recommended for general use based on theoretical foundation, adaptability, ease of use, and ease of result interpretation (Ang 2004). The main alternative methods use the Lasperyes index, preferred by the IEA (Taylor et al. 2010), for which the methodology is arguably more easily understood and explained, but is not as scientific as Divisia methods (Ang 2004). Greening et al. (1997) also found Divisia methods to be the most robust method in a practical test of six different methodologies. The methodology employed here was adapted from the work of Ang (2005). Using the LMDI I method the effect of each factor is given by:

$$\Delta V_{x_k} = L\left(V_i^T, V_i^0\right)\ln\left(\frac{x_{k,i}^T}{x_{k,i}^0}\right) \tag{5-3}$$

where:

$$L(a,b) = \frac{a-b}{\ln a - \ln b} \tag{5-4}$$

If a=b, L(a,b) = a

Taking the general methodology for LMDI I decomposition analysis introduced above and applying it to energy-related carbon emissions, the total change in carbon emissions (ΔC_{tot}), over a time period (*0* to *T*), is a sum of the changes due to changes in production volume (ΔC_{pdn}), changes in inter-sector structure (ΔC_{str}), changes in energy intensity (ΔC_{int}), changes in fuel mix (ΔC_{mix}), and changes in emission factor (ΔC_{emf}).

$$\Delta C_{tot} = C^T - C^0 = \Delta C_{pdn} + \Delta C_{str} + \Delta C_{int} + \Delta C_{mix} + \Delta C_{emf} \tag{5-5}$$

For i subsectors of industry, using j fuels the total carbon emissions can be given by:

$$C = \sum_{ij} C_{ij} = \sum_{ij} Q \frac{Q_i}{Q}\frac{E_i}{Q_i}\frac{E_{ij}}{E_i}\frac{C_{ij}}{E_{ij}} = \sum_i QS_i I_i M_{ij} U_{ij} \tag{5-6}$$

where Q is the output of manufacturing; $S_i (=Q_i/Q)$ and $I_i (=E_i/Q_i)$ are, respectively, the activity share and aggregate energy intensity of subsector i; $M_{ij} (=E_{ij}/E_i)$ is the proportion of energy in subsector i supplied by fuel j, and $U_{ij} (=C_{ij}/E_{ij})$ is the carbon emission factor of fuel j in subsector i. The components of change in equation (5-5) are given by:

$$\Delta C_{pdn} = \sum_{ij} L\left(C_{ij}^T, C_{ij}^0\right)\ln\frac{Q^T}{Q^0} \tag{5-7}$$

$$\Delta C_{str} = \sum_{ij} L\left(C_{ij}^T, C_{ij}^0\right)\ln\frac{S_i^T}{S_i^0} \tag{5-8}$$

$$\Delta C_{int} = \sum_{ij} L\left(C_{ij}^T, C_{ij}^0\right)\ln\frac{I_i^T}{I_i^0} \tag{5-9}$$

$$\Delta C_{mix} = \sum_{ij} L\left(C_{ij}^{T}, C_{ij}^{0}\right) \ln \frac{M_{ij}^{T}}{M_{ij}^{0}} \tag{5-10}$$

$$\Delta C_{emf} = \sum_{ij} L\left(C_{ij}^{T}, C_{ij}^{0}\right) \ln \frac{U_{ij}^{T}}{U_{ij}^{0}} \tag{5-11}$$

where,

$$L\left(C_{ij}^{T}, C_{ij}^{0}\right) = \frac{C_{ij}^{T} - C_{ij}^{0}}{\ln C_{ij}^{T} - \ln C_{ij}^{0}} \tag{5-12}$$

The outputs of equations (5-7) to (5-11) are referred to as the production effect, structural effect, intensity effect, fuel mix effect, and emissions factor effect respectively.

The intensity effect can provide an indication of changes in energy efficiency, whereby a falling intensity effect can indicate an improving efficiency. The decomposed intensity is only an approximate measure of efficiency however. The intensity effect will also include the effects of structural change that occur at a more disaggregate level than that used when splitting manufacturing into subsectors for the decomposition analysis (intra-sector structural change). Additionally energy use at a manufacturing site is not often directly proportional to output, there will usually be a fixed energy overhead related to production (Department of Trade and Industry 1994a). So at a site level if output increases, intensity will tend to decrease, with more output produced for every unit of energy demand. This decreasing intensity can occur with no efficiency improvement at the process level.

There are parts of the analysis presented here where only the energy demand (in final or primary terms), rather than the energy-related carbon emissions, is decomposed. The methodology is similar to that presented above except that only three effects exist, the production effect, structural effect and intensity effect. The definition of these effects are the same, with their influence on the change in energy demand, rather than energy-related carbon emissions, being calculated.

5.2.1 Data and measures used

The manufacturing sector examined here is defined by 2003 SIC codes 15-37, excluding the subsector defined by SIC 23 (Manufacture of coke, refined petroleum products and nuclear fuel). SICs 16 and 37 were unable to be included in the decomposition analysis, for reasons discussed below. Energy demand is measured in terms of Gross Calorific Value (GCV), and final energy demand, obtained from the 'Digest of United Kingdom Energy Statistics' (DUKES) (DECC 2012b) and 'Energy Consumption in the UK' (ECUK) (DECC 2011d). Energy use was split between seven different fuels, as detailed in Table 5-5 below. Measuring energy in terms of final demand means that improvements in electricity generation, both in terms of generation efficiency and carbon emissions factor of the fuels utilised are encapsulated in the emission factor effect *(ΔC_{emf})*. Due to limitations of the data used the use of combined heat and power (CHP) by some subsectors and the reduced primary energy use and emissions this entails cannot be accounted for. All electricity demand is assumed to be supplied by the national grid. Only the emission factor of electricity is varied in this study, with other fuels' emissions factors held constant, this is approximately true. Measuring the useful output of a manufacturing subsector when constructing an efficiency indicator is a topic that has received considerable and is discussed in more depth in section 2.3. Output here is measured in value of production due to data availability and the factors discussed in Chapter 2.

5.2.2 Timescale and disaggregation level of analysis

Some studies have found the level of sectoral disaggregation used in a decomposition analysis can significantly affect results (Ang and Skea 1994, Fisher-Vanden et al. 2004). Structural change, for example, can be underestimated if analysis is not undertaken at a high enough level of disaggregation (Fisher-Vanden et al. 2004, Jenne and Cattell 1983). As discussed above, these extra structural contributions not encapsulated in the reported structural effect will instead be included in the intensity effect. This can give a false impression of the changes in efficiency. Analysis was conducted at the highest level of disaggregation possible with the data utilised. This resulted in the manufacturing sector being split to 22 subsectors, based on the 2003 SIC system (Office of National Statistics 2002). It would be desirable to perform the analysis with a higher level of subsector disaggregation. Suitable data that would allow this were restricted in timescale however, and so not appropriate for this study. The results shown here are specific to the data used (including the level of disaggregation) and methodology used. Different results and conclusions could be reached if these varied.

The decomposition analysis covered the time period 1990-2009. Due to methodological changes in the collection of energy data (BERR 1998, 2007) over the periods 1995-1996, 1998-1999 and 2000-2001, analysis could not span all years[15]. The recycling subsector (SIC 37) could not be included in the decomposition analysis due to a lack of output data. The tobacco sector (SIC 16) was also omitted due to concerns about the accuracy of data (see Chapter 4). Twenty subsectors were therefore included in the full analysis. The split into EI and NEI subsectors is taken from the previous chapter (Chapter 4). Due to the timescale of analysis and other data restrictions the higher aggregation level results were used for the split into EI and NEI subsectors.

[15] These methodological differences are detailed in Appendix 2.

5.3 RESULTS

The results for the decomposition of carbon emissions are graphically represented here (Fig. 5-2 to Fig. 5-4), the results for decomposition of final and primary energy are tabulated (in addition to the decomposition results of carbon emissions, see Table 5-1 to Table 5-3). The total change in carbon emissions (Tot) is separated into the effect of changes in production (Pdn), structure (Str), energy intensity (Int), fuel mix (Mix), and emissions factor (Emf). For the final energy and primary energy cases only the first three effects contribute. The pattern of change throughout the time period for the three effects contributing to the changes in energy demand are similar for both final and primary energy to those seen for carbon, the graphical representation of the final and primary energy demand decomposition is therefore omitted for conciseness. The dotted lines in Fig. 5-2 to Fig. 5-4 indicate those periods that cannot be directly compared due to methodological changes in the compilation of datasets. The values shown in Fig. 5-2 to Fig. 5-4 are the cumulative change since 1990, shown as a percentage relative to the level of carbon emissions in 1990.

Fig. 5-2 shows a decomposition of carbon emissions from the entire manufacturing sector at a 2 digit SIC level of disaggregation for 1990-2009. The effect of alteration in the fuel mix has had a net positive effect on the carbon emissions over the period. The bulk of the effect due to fuel mix has been since 2001. This is mainly caused by an increase in the proportion of electricity use (DECC 2011b), which has a higher emission factor than other fuels, this higher emission factor primarily being due to the losses involved when generating and transporting centrally generated electricity. The changes in electricity emissions factor (specifically in the years up to 2000) have caused a reduction in energy-related carbon emissions. This decline in electricity emissions factor was primarily caused by an increase in the use of natural gas in electricity generation (and a corresponding decline in the use of coal and oil) during the 1990s (DECC 2011b): the so called ‘dash for gas’. A slight increase in emissions factor after this period was caused by a decrease of nuclear in the generation mix (DECC 2011b). Prior to 2000 the reduction in the emissions factor of electricity limited the effect seen in shifts of the fuel mix towards electricity, whilst post 2000 the increase in emissions factor has accentuated the fuel mix effect due to an increase in electricity use.

The effect of changes in production on carbon emissions has been varied over the time period studied. During the early 1990s there was a recession in the UK, causing the negative contribution to emissions from the production effect. The most recent recession (2008-present) has caused a similar effect, reducing emissions. Between these periods of recession (1992-2007) the effect of changes in production increased the energy-related carbon emissions. Overall the production effect has had a negative effect (see Fig. 5-2 and Table 5-1, Table 5-2, Table 5-3). How the manufacturing recovers from the most recent recession could have a large impact on future emissions.

Structural effects have had some negative effect over the time period, causing a reduction in energy demand. This indicates a movement of the sector from manufacturing sectors with higher energy intensity to subsectors with lower energy intensity. Most of this structural effect appears to be over the latter half of the period studied. The bulk of the decrease in carbon emissions is caused by a decline in energy intensity. This can indicate an improving energy efficiency and is discussed in more detail in section 5.4.

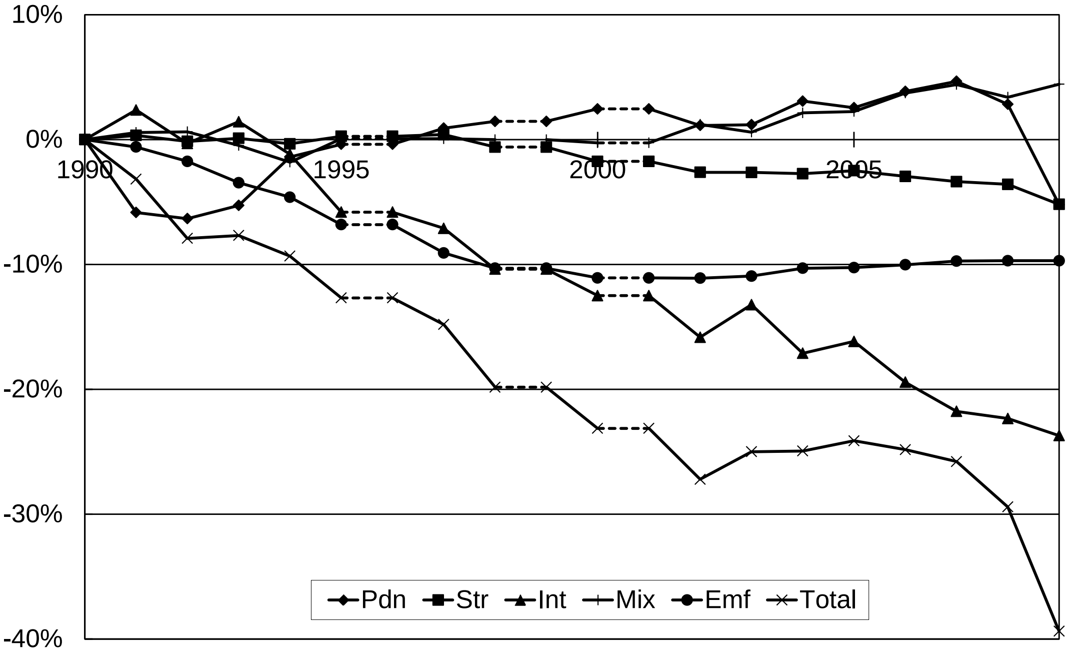

Fig. 5-2: Decomposition of carbon emissions in the UK manufacturing sector, 1990-2009.

It is interesting to consider the EI and NEI sub-sectors (as defined in Chapter 4) separately for the decomposition analysis. Fig. 5-3 shows the results for only the EI sub-sector and Fig. 5-4 those for only the NEI sub-sector (with corresponding numerical results in Table 5-1). Note the results in Fig. 5-3 and Fig. 5-4 are both shown in relation to the carbon emissions of the corresponding sub-sector in 1990, it is these relative changes that are of most interest for comparison. Fig. 5-5 shows the mean absolute annual change in carbon emissions.

Comparing Fig. 5-3 and Fig. 5-4 (and Table 5-1) it can be seen that the NEI sub-sector has made more substantial relative reductions in its carbon emissions over the period 1990-2009 and this is mainly due to a much greater relative reduction in the intensity effect over this period (indicating an improving efficiency). This is surprising as the EI subsector has been modelled so that it has stronger drivers to efficiency than the NEI subsector. This is an important finding and is discussed in more detail in section 5.4.5. The production effect has had a greater effect on increasing emissions in the EI subsector in relation to the NEI subsector. This is also a somewhat surprising result given that at a sector level structural changes have decreased emissions (see Fig. 5-2). This therefore indicates that the structural changes have been more from a restructuring within the EI and NEI subsectors than a move in overall production towards the NEI subsector. This is confirmed by the substantial structural effect seen in the EI subsector, whilst structural change has had negligible effect in the NEI subsector. The majority of the structural effect seen at the sector level is therefore caused by a shift towards subsectors with a lower energy intensity, that are within the EI subsector.

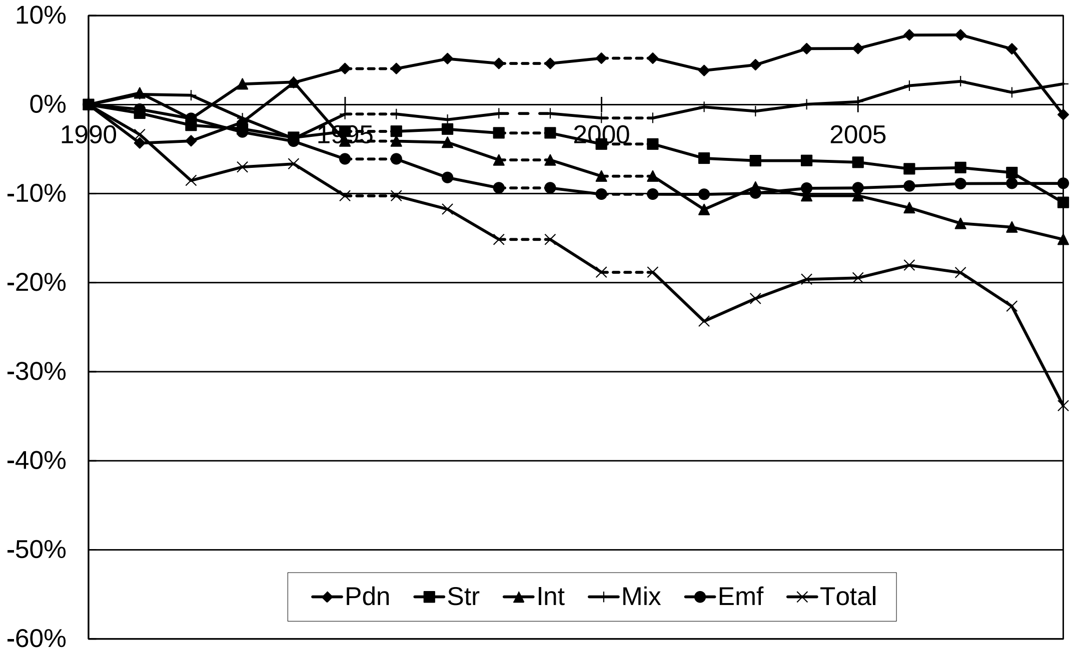

Fig. 5-3: Decomposition of carbon emissions in the EI subsector of manufacturing, 1990-2009.

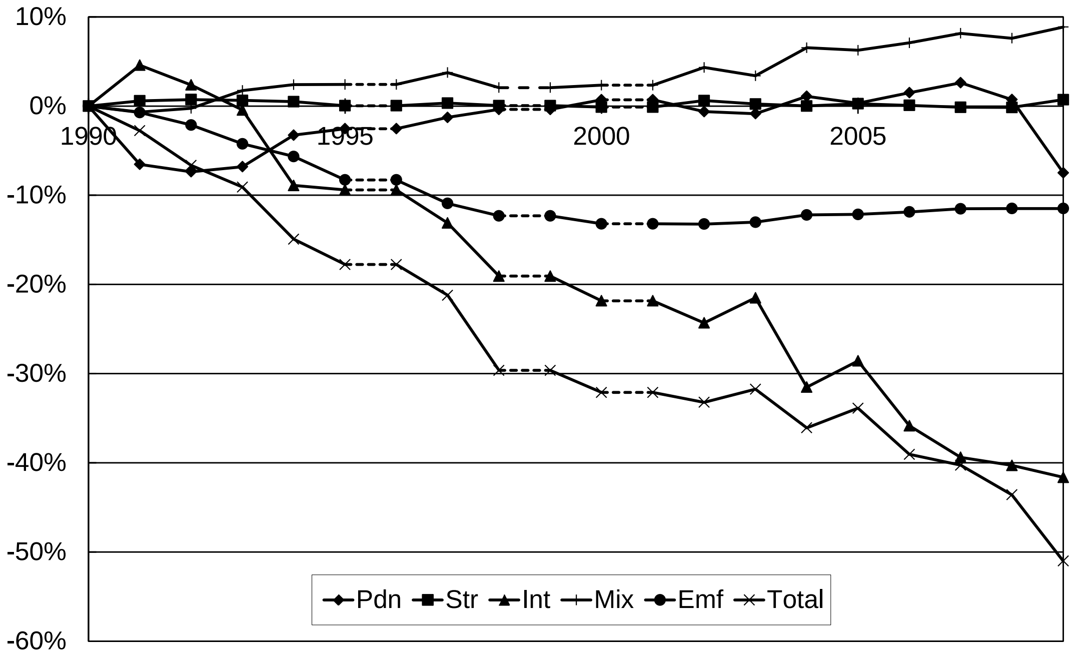

Fig. 5-4: Decomposition of carbon emissions in the NEI subsector of manufacturing, 1990-2009.

Fig. 5-5 shows the EI sub-sector has also made greater absolute reductions in its emissions over the time period analysed, despite significantly greater relative reductions in the NEI subsector.

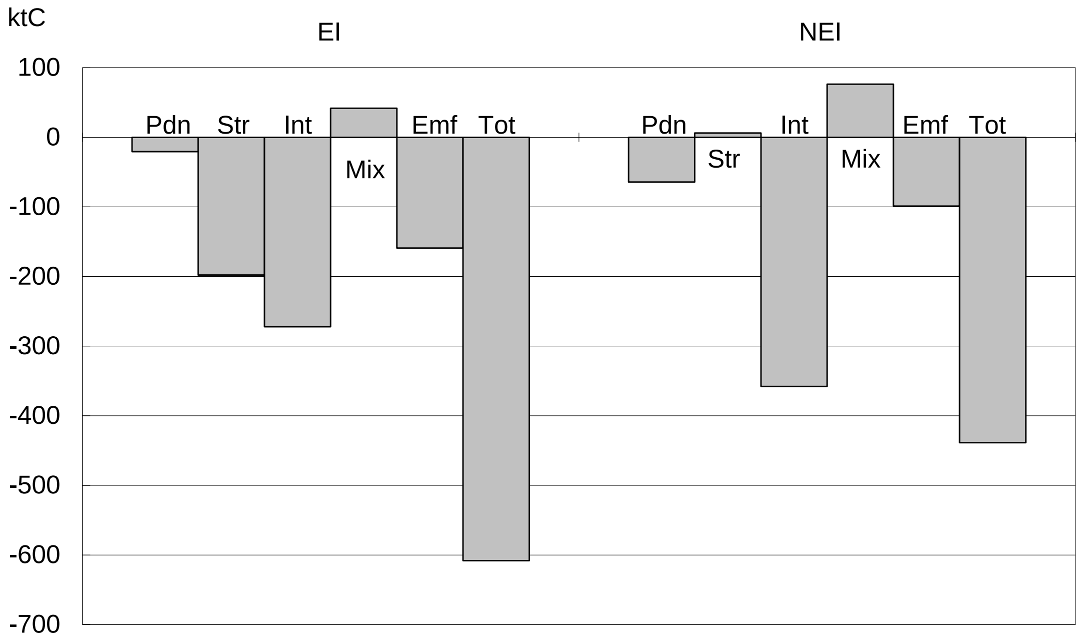

Fig. 5-5: Mean annual change in carbon emissions of the EI and NEI subsectors, 1990-2009.

Table 5-1 summarises the information in Fig. 5-2, Fig. 5-3 and Fig. 5-4. Table 5-2 and Table 5-3 show the results of a decomposition of primary energy demand and final energy demand, respectively.

	Whole Sector	EI sub-sector	NEI sub-sector
Pdn	-0.5%	-0.2%	-0.7%
Str	-0.4%	-0.9%	0.1%
Int	-1.8%	-1.1%	-3.3%
Mix	0.4%	0.2%	0.7%
Emf	-0.7%	-0.6%	-0.8%
Total	-3.0%	-2.6%	-4.0%

Table 5-1: Mean annual change in carbon emissions of the manufacturing sector and subsectors, 1990-2009. Results are given as a percentage of the previous year's total.

	Whole Sector	EI sub-sector	NEI sub-sector
Pdn	-0.5%	-0.2%	-0.6%
Str	-0.3%	-0.6%	-0.1%
Int	-1.8%	-1.1%	-3.0%
Total	-2.5%	-2.0%	-3.5%

Table 5-2: Mean annual change in primary energy demand of the manufacturing sector and subsectors, 1990-2009. Results are given as a percentage of the previous year's total.

	Whole Sector	**EI sub-sector**	**NEI sub-sector**
Pdn	-0.5%	-0.2%	-0.6%
Str	-0.3%	-0.7%	0.1%
Int	-1.9%	-1.2%	-3.3%
Total	-2.7%	-2.0%	-3.9%

Table 5-3: Mean annual change in final energy demand of the manufacturing sector and subsectors, 1990-2009. Results are given as a percentage of the previous year's total.

5.4 DISCUSSION

The results seen in section 5.3 are further discussed here, putting them into historical context and examining the effect that production growth, variations in energy price, and fuel switching may have had on the results seen, with particular reference to their influence on the intensity effect. The differences seen between the EI and NEI subsector are also further examined.

5.4.1 Historical context

It is useful to place the current results in a historic context. Energy use first became an important issue for many companies following the first, so called, oil crisis in 1973, and the subsequent energy price rise (see Fig. 5-6). Although the data used for the main analysis does not cover the period prior to 1990, previous studies and data have covered the period 1973-1990.

Table 5-4 shows the results from a decomposition analysis, published by the former Department of Trade and Industry (DTI) in Energy Paper 64 (EP64) (Department of Trade and Industry 1994a). These cannot be directly compared to those of the current study, due to differences in methodology and datasets. The EP64 analysis also only covers final energy demand, rather than carbon emissions. However, general trends can be extracted in order to aid the understanding of the results from the current study. EP64 is not the only study that carried out a decomposition analysis of the UK industrial sector pre-1990 (Greening et al. 1998, Greening et al. 1997, Howarth et al. 1991, Jenne and Cattell 1983, Liaskas et al. 2000, Park et al. 1993, Schipper et al. 2001, Unander 2007, Unander et al. 1999). The results from EP64 were presented in a form that could be most easily extracted for comparison purposes and the analysis was also undertaken at the greatest level of disaggregation. Other studies are generally in agreement in the main trends seen here[16].

It can be seen from Table 5-4 that prior to 1990 there has been an overall reduction in energy demand from the manufacturing sector. As in the post 1990 period the main contributor is a falling energy intensity, with structural change having a relatively small impact in reducing energy demand. There were also significant falls in pre-1990 production (up until the mid-1980s). The greatest period of energy demand reduction was 1979-1984, where the largest relative annual drops seen due to the production, intensity and structural effect, combined to give by far the greatest reduction in energy demand seen in the twenty year period from 1973-1993.

16 There is some disagreement over the importance of structural changes, see Section 5.4.3.

	1973-1979	1979-1984	1984-1989	1989-1993
Production	-0.8%	-1.9%	4.3%	-1.1%
Structure	0.0%	-1.2%	-0.3%	-0.5%
Intensity	-0.8%	-4.4%	-3.0%	0.7%
Total	-1.5%	-7.5%	1.0%	-0.9%

Table 5-4: Decomposition of final energy demand, 1973-1993, adapted from EP64 (Department of Trade and Industry 1994a) . Annual change in the final energy demand is shown, given as a percentage of the mean energy demand over the period.

5.4.2 Production growth

As manufacturing output rises, intensity is often observed to improve. An increase in output is usually coupled with investment in new plant, new equipment is generally more efficient than older equipment, and so intensity improves (Greening et al. 1998, Jenne and Cattell 1983) (assuming no significant change in intra-sector structure). In relation to the drivers and barriers discussed in Chapter 4 a period of growth may decrease the significance of some barriers, in particular lack of capital and a focus on production would likely be greater in a period of recession. The results shown in Fig. 5-2, Fig. 5-3 and Fig. 5-4 support this idea, to some extent. In the early 1990s a recession caused production to fall, in this period the intensity effect was minimal. After the initial recovery as production grew, intensity decreased. There is not a simple relationship between growth and intensity however. Part of the decrease in intensity may be due to the presence of an energy overhead, as discussed in section 0 above. Also if a decrease in production led to plant closures it is likely that older, less efficient, plants are closed first and so a decreasing intensity could be linked to a decreasing production. The so-called 'rebound effect' may also provide a link between increases in efficiency (which are shown as decreasing energy intensity) and output. The rebound effect is discussed in reference to manufacturing in section 4.1.2.1. In the context of the results presented here some increase in production could be caused by the falling intensity as reducing energy use through improving intensity may put a company in a stronger position to manufacture more product. It is however difficult to quantify any rebound effect or separate the effect from other factors. The link between production growth and energy intensity is not always consistent. Table 5-4 shows that production decreases were coupled with falling intensity between 1973 and 1984, particularly so in the second half of this period. During the recent production drop (2007-2009) the intensity effect is seen to follow a similar trend to that before the recession (see Fig. 5-2). The effect of production growth is therefore unclear but with other factors being constant a fall in intensity would appear to be the most likely outcome during a period of growth.

5.4.3 Energy price

Higher energy prices increase the financial benefits of reducing energy use, and so can act as a strong driver for energy saving measures (see Chapter 4). Fig. 5-6 shows how energy price in the industrial sector has varied between 1970 and 2009, for a number of fuels and for the annually weighted total fuel price. Over the majority of the period studied here (1990-2009) energy prices have been lower, in real terms, than for the previous two decades. Prices tend to have fallen during the 1990s, although in the late 2000s have risen to levels comparable to the peaks of the early 1980s. Fig. 5-7 shows projections of prices paid by industry for gas and electricity. A continued increase in energy prices is expected, strengthening their driving effect.

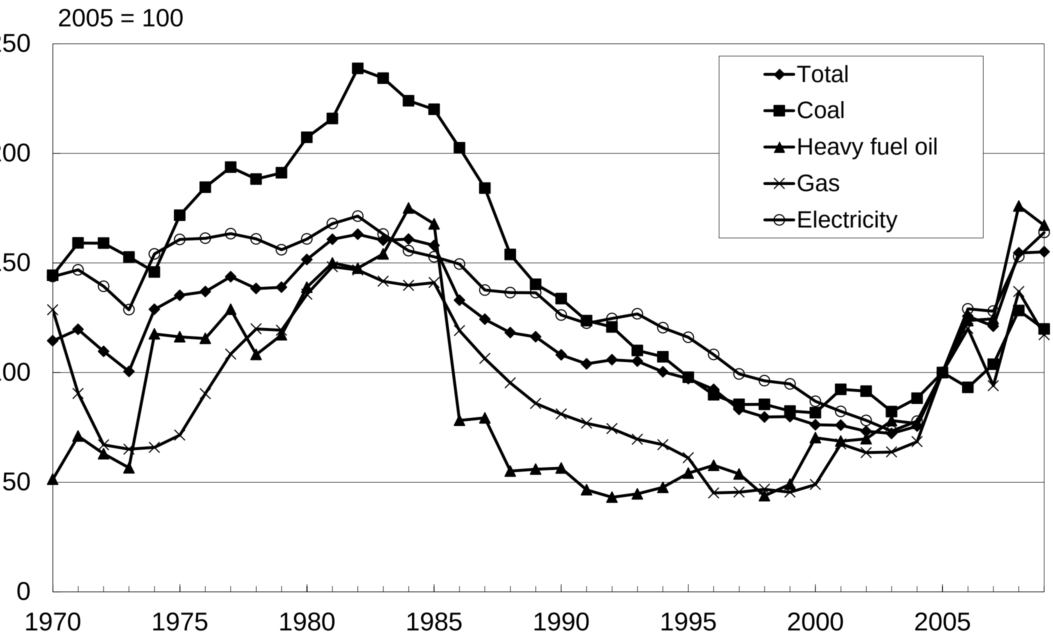

Fig. 5-6 Fuel price index for the industrial sector, relative to GDP deflator, 1970-2009. Indexed to 2005. Adapted from QEP (DECC 2010g). [NB: This includes the Climate Change Levy (CCL) from April 2001.]

It appears that in the current study energy prices have had little impact, Fig. 5-2 to Fig. 5-4 show fairly constant reductions in the intensity effect (ignoring small annual fluctuations), outside the periods of recession. Decreases in energy price during the 1990s were coupled with a continuing decrease in energy intensity. The effect of recent price rises may be yet to be seen, due to a delay, or lag, between price rises and companies taking action to improve their efficiency. This seems to be reasonable conjecture. It may take a sustained period of high prices to cause a reaction from the manufacturing sector, and the projects that result from this may take some time to be implemented (Greening et al. 1998). The effect that would be seen is further complicated by the recent recession and the interaction of other effects that act to increase or decrease energy intensity. The results shown in Table 5-4 can be used to examine the effects of energy prices pre-1990. The greatest intensity improvements were seen in the period 1979-1984, and 1984-1989. Fig. 5-6 shows that energy prices started to increase sharply in 1973, peaking in 1984, and falling thereafter until the most recent rise. This could be used to support the idea that there may be a delay between an increase in prices and the reaction (characterised by lowered intensity) of industry, although other factors may have influenced the intensity effect during this period.

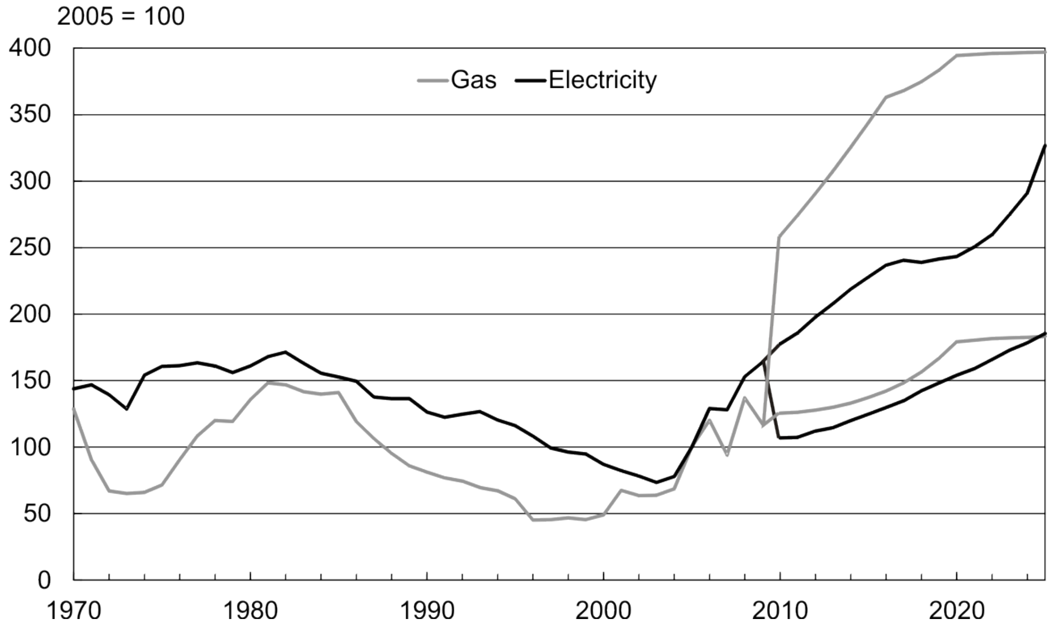

Fig. 5-7: Industrial electricity and gas prices indexed to 2005. From 2010 price projections are shown for low and high scenarios (DECC 2010f).

Conflicting reports regarding the influence of energy prices on intensity can be found in literature. Howarth et al. (1991) examined the link between price and energy intensity improvements in eight OECD countries. They found that intensity did not increase more rapidly when energy prices were high. In fact the greatest improvements were often seen when energy prices were low and growth was stimulated. This growth led, as discussed above in section 5.4.2 to lowered intensity. Conversely, Greening et al. (1998) found a link between large falls in energy intensity and increasing prices. There is a recognition that the rates of energy intensity decrease throughout sectors of the economy and across countries have been lower since 1990, than between 1973 and 1990 (Taylor et al. 2010). It appears that the high energy prices pre-1990 constituted a greater driver to reducing energy intensity than the environmental concerns that have become more important since 1990 (Unander 2005). Energy prices can also influence the structure of industry as rising prices encourage a move towards subsectors of manufacturing with lower energy intensity (Jenne and Cattell 1983). It is difficult to draw any conclusions on the effect of energy price on either production or structural changes over the period studied as prices have been relatively low (until the more recent period) and there has been no strong effects due to structural change. Prior to 1990 periods of high energy prices corresponded with falls in production, with the only period of output growth, 1984-1989, coupled with a drop in energy prices (see Table 5-4 and Fig. 5-6). There is some disagreement in the literature over the influence structural changes had on industrial energy demand following the first oil crisis [compare for example Jenne and Cattell (1983) to Department of Trade and Industry (1994a) and Howarth et al. (1991)] and so the picture is not clear in this regard.

Increasing energy prices through policy, either directly or through options that penalise emissions, is a common method used by governments to encourage more efficient use of energy in manufacturing, see the discussion of policy in Chapter 4. However, this is a difficult balancing act, as discussed above high prices may not necessarily lead to lower intensity as high prices can also limit growth (which can harm improvements in intensity) and lead to carbon leakage (as discussed in Chapter 4).

5.4.4 Fuel switching

Falls in energy intensity can be due to fuel switching. For example natural gas can usually be used more efficiently than coal due to the greater control afforded. Adams and Miovic (1968) noted this effect as being partly responsible for a falling energy intensity, despite falling energy prices, in their study of Western Europe. Table 5-5 shows the change in fuel mix over the period 1990-2009 for the UK industrial sector, as studied here. Increases in the proportions of natural gas and electricity used could be responsible for some of the intensity improvement observed. In the case of electricity this potential intensity improvement is offset from an emissions perspective by electricity having a greater emissions factor than other fuels (see section 5.3). Future decarbonisation of electricity generation may also make electricity attractive from a carbon emissions perspective. The shifts in fuel mix can be influenced by the fluctuations in price of individual fuels. During the 1990s all the major fuels except oil showed significant price falls (see Fig. 5-6). This can partly explain the move away from oil as a fuel in the manufacturing sector. Coal although also falling in price has other disadvantages, requiring additional transport and storage requirements (Greening et al. 1998).

	EI		**NEI**		**Total**	
Fuel	**1990**	**2009**	**1990**	**2009**	**1990**	**2009**
Coal	14%	11%	5%	1%	11%	8%
Natural gas	32%	38%	39%	48%	34%	41%
Manuf. fuel	20%	12%	0%	0%	13%	8%
LPG	2%	0%	2%	0%	2%	0%
Fuel oil	9%	2%	13%	2%	10%	2%
Gas oil	3%	7%	13%	8%	6%	7%
Electricity	21%	30%	27%	42%	23%	34%

Table 5-5: The fuel mix of the manufacturing sector, the EI and NEI subsectors. 1990 and 2009.

5.4.5 The energy-intensive and non-energy-intensive subsector

The improved relative performance of the NEI subsector in reducing energy-related carbon emissions, particularly though decreased intensity is examined further here. In comparison to the current work a study of the Netherlands (Ramirez et al. 2005) took a similar approach in separating the non-energy-intensive subsector for a decomposition analysis over the years 1988-1999. In the study of Ramirez et al. (2005) it was found that there was no improvement in the decomposed energy intensity over the period investigated. A very different outcome is therefore seen here, for the UK.

A greater level of fuel switching in the NEI subsector (see Table 5-5) can partly explain the greater comparative improvements in intensity, compared to the EI subsector. Also as energy prices have been relatively low over the majority of the period studied the increased drivers to energy efficiency in the EI subsector would not be as strong as they would be under a period of high prices. The NEI subsector has shown less production growth however, which is often linked to intensity reductions, see section 5.4.2. Additional reasons for the intensity improvement in the NEI subsector are therefore sought, and the period prior to 1990 is examined to provide some insight.

It was possible to undertake some additional analysis using the same measure of output as for the core study and energy demand data from EP64 (Department of Trade and Industry 1994b). This analysis consisted of decomposing final energy demand into the effects of changes in production, structure, and intensity. The analysis was limited to two discrete five year periods, 1979-1984 and 1984-1989, due to data availability. Results are not directly comparable with the post 1990 period as energy data is drawn from a different source. However results from this analysis should be sufficient to examine any large differences between the EI and NEI subsectors pre-1990. The associated results from this analysis are shown in Table 5-6.

	1979-1984		**1984-1989**	
	EI subsector	NEI subsector	EI subsector	NEI subsector
Production	-2.0%	-2.2%	4.4%	3.6%
Structure	-0.1%	0.5%	-0.2%	-0.4%
Intensity	-7.2%	-2.9%	-3.4%	-1.4%
Total	-9.3%	-4.6%	0.7%	1.8%

Table 5-6: Decomposition of final energy demand, in the EI and NEI subsector, 1979-1989. Annual change in the final energy demand is shown, given as a percentage of the mean energy demand over the period.

The structural and output effects are similar between the two subsectors over the earlier time period examined in Table 5-6, but the intensity effect indicates that the EI subsector made much larger relative improvements between 1979 and 1989 in comparison with the NEI subsector. For any company, or subsector of industry, there tends to be a number of opportunities for saving energy that are relatively easy to implement and have attractive economics. These are sometimes referred to as 'low hanging fruit', the barriers to their implementation are not as strong as for other efficiency measures. One possibility for the better energy intensity performance seen in the NEI subsector, is that due to the notionally stronger drivers to reducing energy intensity in the EI subsector, it made greater intensity improvements pre-1990, in comparison to the NEI subsector. Consequently within the NEI subsector there may have been relatively easier options to improve energy intensity over the period 1990-2009, in comparison to the EI subsector. Findings from a recent DECC study (DECC 2012h) support this, observing that energy intensive industry is reaching the limits of what can be achieved through efficiency (which is driven by high fuel prices) and that there may be more potential in the less energy intensive subsectors. Examining the whole manufacturing sector there is evidence from previous studies for energy intensity improvements slowing since the late-1980s, both within the UK and more widely in other developed nations (Unander 2007, Unander et al. 1999). Part of this trend may result from the fact that opportunities for improving intensity are becoming more difficult to realise (Unander 2005). This does not mean energy intensity improvement has 'run its course'. Further potential improvements in energy efficiency within manufacturing have been identified and discussed in other chapters of the current work. This decomposition analysis does suggest that significant future improvements may require substantial process redesign and material substitution (Von Weizacker et al. 1997), rather than relying on, relatively small, continual improvements in efficiency however (HM Government 2010). These continual improvements are becoming more difficult to realise and the potential gains are not as great as was previously enjoyed. This is an area where policy can have influence, as discussed in Chapter 4, by driving these more difficult to reach improvements.

5.5 SUMMARY

Energy-related carbon emissions from UK manufacturing have fallen by approximately 3% per annum over the period 1990 to 2009. The principal reason for this drop was found through a decomposition analysis to be a decreasing energy intensity in the manufacturing sector, indicating an improving energy efficiency. The EI and NEI subsectors (defined in Chapter 4) were also analysed separately. The EI subsector, which had notionally greater drivers to reducing energy-related carbon emissions, was found to have shown significantly less relative progress than the NEI subsector in terms of both a reduction in energy-related carbon emissions and in reducing intensity.

Energy prices have generally been falling over the period of the study, being low in relation to previous decades. These relatively low prices appear to have had little influence on changes in intensity. Some of the improvement in intensity observed may have been stimulated by growth in manufacturing and the new facilities and equipment this entails. It is also thought that some of the intensity improvement was due to fuel switching, towards electricity and natural gas, which can generally be used more efficiently than other fuels. Improvements in energy intensity could also be due to more efficient technology being employed, better control and housekeeping, or due to a change in the feedstock (utilising a higher proportion of recycled materials). Additionally intra-sector structural change may cause changes in energy intensity. The better performance of the NEI subsector seen here is thought to be partly due to the EI subsector showing greater improvements in energy intensity in the pre-1990 period. As energy intensity reductions are made the easier options (the 'low hanging fruit') are taken first, and so further intensity improvements can be more challenging. As discussed in Chapter 4 the previous improvements made in a technology can influence the technical and economic potential improvements, they can also influence the strength of certain barriers that can prevent the economic potential being achieved.

The analysis conducted here is from a broad, top-down perspective. It therefore covers the manufacturing sector as a whole and can indicate general trends, but cannot determine the real efficiency (rather than intensity) gains made at a subsector level. A limitation on any decomposition, or top down study, is the level of disaggregation, methodology and data used. No study of this type can supply indisputable results. Regardless of methodology employed, and data available, such techniques only give a representation of previous changes. This is not to say the results are not valid however, and studies such as that performed here contribute to a better understanding of historical changes, which can inform the analysis of future improvement opportunities. In the case of the current work there is reasonable confidence in the main trends discovered and the implications of these. The precise contribution of each of the effects is subject to a higher level of uncertainty however.

CHAPTER 6

WASTE HEAT RECOVERY

Heating processes represent approximately 70% of final energy demand in UK manufacturing (DECC 2010d). A significant proportion of this heat input is available in the exhaust from processes, and other output streams. There is scope to recover some of this currently wasted heat and use it to fulfil energy demands. Using this surplus heat as an energy source can displace fossil fuel based energy sources and so can contribute to meeting the twin objectives of reducing carbon emissions and increasing energy security.

The technical potential for waste heat recovery in UK industry has previously been estimated in work for which the current writer was a co-author (McKenna and Norman 2010, McKenna et al. 2009), one of these publications is included in the Appendix 6. This previous work was undertaken using the database, introduced in Chapter 3, that was built from the National Allocation Plan (NAP) of the EU Emissions Trading System (EU ETS). This previous work estimated site level energy demands and heat recovery potentials. An important part of this work was that information was supplied on the temperature of the expected heat demands and recovery potentials, and their location. This information was used in the current chapter to provide an indicative picture of what proportion of the identified technical heat recovery potential could be utilised by a range of technologies. The original work (McKenna and Norman 2010) although identifying the technical heat recovery potential did not specify a use for the waste heat.

The waste heat identified can be used to fulfil a heating demand on-site at a temperature below the recovery temperature (using a heat exchanger or similar technology), with heat pump technology the heat can be upgraded to a higher temperature to meet a corresponding demand. Heat can also be converted to provide electrical power or a cooling demand. Finally heat can be exported to meet off-site heat demands. The proportion of the heat recovery potential that could be utilised in each of these areas is estimated in this chapter. The technical potential for the different applications is assessed here, the economics are not examined beyond basic qualitative considerations. The theory and practical considerations in utilising waste heat for these end uses are first examined and this is used to inform a methodology for estimating the waste heat that can be utilised in each end use. The results from the analysis are presented and discussed in the context of wider drivers and barriers to realising this potential. The current chapter is an extended version of a paper presented at the Fourth International Conference on Applied Energy (ICAE2012), for which the current writer was the lead author (Hammond and Norman 2012b), the paper is reproduced in Appendix 6.

6.1 RECOVERING HEAT – THEORETICAL AND PRACTICAL CONSIDERATIONS

The First Law of Thermodynamics tells us that energy is not created or destroyed, but conserved (see Chapter 2). With respect to heating processes this implies that the heat energy supplied must be stored in the product, converted to another form, or is lost to the environment. The Second Law of Thermodynamics and exergy considerations tell us that the quality of energy must reduce in any real process. In relation to heating processes, this means that combustion gases must be at a temperature above the heat requirement of the process, for heat transfer to occur, and if no heat recovery measures are used there will be waste heat arising. As an example consider a reverberatory furnace used in aluminium melting, the minimum possible temperature of gases immediately exiting the furnace corresponds to the aluminium pouring temperature of 650-750°C. Even at this minimum operating condition at least 40% of energy input is lost as waste heat if no recovery measures are installed (US DOE 2008). Generally heat is lost to the environment in flue gases, through furnace walls, and in the heated product. In certain cases this heat can be recovered and used as an energy source, displacing the use of conventional fuels, therefore potentially providing economic savings, limiting the environmental impact caused by the use of conventional fuels, and conserving these resources. In this section the theory and practical considerations of various technologies for reusing waste heat are examined. This includes heat exchangers, heat pumps, heat-to-power equipment and technology used for transporting heat.

6.1.1 Heat exchangers

The simplest and usually most economical method of heat recovery is to directly mix the source of heat with a heat sink. An example of this is the recirculation of exhaust gases from an oven to the inlet air. This reduces the heat that is required from a conventional heat source in raising the inlet air to the temperature of the oven. This approach requires only basic control and equipment, such as a fan and some ducting. In many cases however it is not possible to mix the two streams of the source and sink directly as it would cause contamination of some kind, if this is the case a heat exchanger is required to allow heat transfer between two fluids, whilst maintaining separation between the fluids.

Various types of heat exchanger exist, for example see Shah et al. (2003) Goldstick and Thumnann (1983), and the Carbon Trust (1996) for discussion on the different types and classifications. The choice of heat exchanger is dependent on many factors including the temperature of the source, the drop to the sink temperature, phase of the source and sink flows, moisture content and corrosiveness of the streams, whether any cross contamination of the streams is allowable, variation in the flows, the allowed size of the exchanger, potential to retrofit, cost, efficiency, operating times, pressure of the streams, and ease of cleaning and maintenance (Carbon Trust 1996, Goldstick and Thumnann 1983). The use of a certain type of heat exchanger needs to be judged on a case-by-case basis and is a common problem (Ammar et al. 2012). Tools have been developed to assist in the selection of a heat exchanger for a certain heat recovery situation (Teke et al.

2010). Heat exchangers are used for heat recovery from fluids, to recover heat from a solid (which is much less common) a fluid is usually passed over the solid, so that heat is first transferred to the fluid. The choice of heat exchanger that would be made for a given situation is not considered further here as it is the application of the technology that is of interest.

Fig. 6-1 shows a very simple schematic of a counter flow heat exchanger of the shell and tube type. In this example a hot fluid is passed through the central tube that transfers heat to the fluid passing through the shell of the heat exchanger. The enthalpies of the heat source going into (H_{A1}) and exiting (H_{A2}) the exchanger and similarly of the sink entering (H_{B1}) and exiting (H_{B2}) the exchanger are labelled.

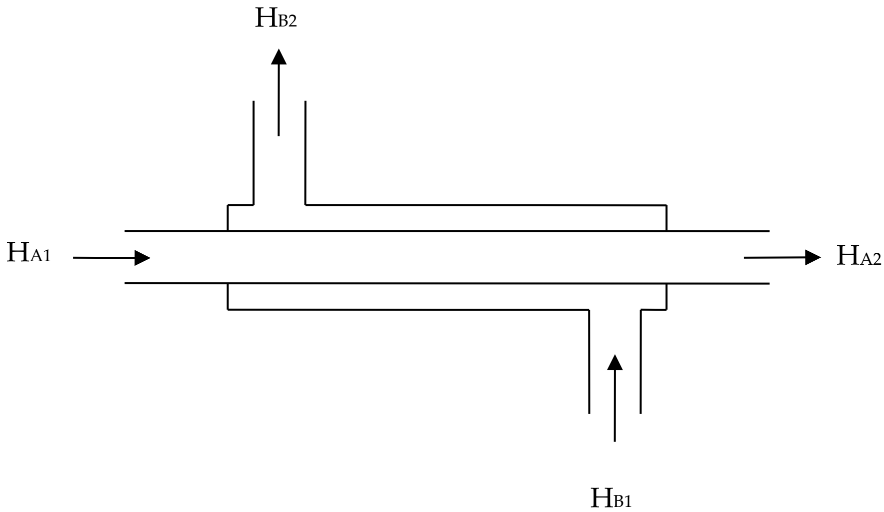

Fig. 6-1: Simple schematic of a shell and tube, counter-flow, heat exchanger.

The mass of each fluid is conserved as it passes through the heat exchanger. Assuming no heat losses from the heat exchanger (the ideal case) the change in enthalpy in the source fluid (A) is equal to the change in enthalpy of the sink fluid (B). As in equation (2-2):

$$H_{A1} - H_{A2} = H_{B2} - H_{B1} \tag{6-1}$$

The heat transfer taking place in a heat exchanger is defined by equation (6-2) (US DOE 2008).

$$\dot{Q} = UA\Delta T \tag{6-2}$$

$\dot{Q}$ is the heat transfer occurring in the heat exchanger. U is the heat transfer coefficient of the heat exchanger, which is dependent on the exchanger design and materials, and the characteristics of the fluids involved, including their temperature. ΔT is a function of the temperatures of the fluid streams in the heat exchanger, it is often calculated using the Log Mean Temperature Difference (Bejan et al. 1996), this generally increases as the temperature difference between the fluids increases. A is the area of the heat exchanger. Therefore for a given heat exchanger construction and fluids, heat transfer rate is maximised when the area and the temperature difference between the fluids are greatest. As the area of the heat exchanger increases so does the cost, there may also be practical considerations in physically fitting the exchanger into the production area. The difference in temperature that can be achieved in practice is limited by the minimum and maximum allowable temperatures in the exchanger (see below) as well as the required temperature of the sink outlet and the available inlet temperatures from both the heat source and sink.

There are operating temperature restrictions imposed by the materials used in heat exchangers, and the composition of the waste streams. At high temperatures corrosion and oxidisation of the heat exchanger are accelerated. Oxidisation occurs at temperatures above 425°C for carbon steel and 650°C for stainless steel, advanced alloys can be used up to 900°C and above this temperature ceramic materials can be used (US DOE 2008). The materials required for higher temperature recovery are more costly. Air bleeding can be used to lower the temperature of exhaust gases to a usable level. Dilution air bled into the exhaust gas will reduce the thermodynamic quality of the waste heat (by reducing the temperature), although the quantity of waste heat remains constant (US DOE 2008). This is therefore inefficient form an exergetic perspective, as thermodynamic quality is lost, but in practice can be required to effectively utilise a heat source. There is also a lower temperature bound for which heat recovery is possible. If exhaust gases are cooled below their dew point temperature water vapour will condense and can deposit corrosive substances on the heat exchanger (US DOE 2008). The minimum temperature to avoid this corrosion is dependent on the fuel used and the process related chemicals in the exhaust, usually ranging from 120°C to 175°C (US DOE 2008). Below these temperatures recovery is available with more advanced materials and technologies, that limit the corrosive effects (US DOE 2008). This comes at higher cost however and maintenance requirements are often higher for low temperature heat exchangers. The latent heat[17] released by condensing the water in the waste heat streams contains a significant portion of the enthalpy in the exhaust gases (US DOE 2008). The heat available for recovery is therefore limited by the lower temperature bound of the recovery.

The composition of the waste heat source affects the materials used in heat exchangers as the source fluids can be corrosive. Additionally heat transfer rates are affected by the composition of the waste heat and recovery streams. Denser fluids have higher heat transfer coefficients and so enable higher heat transfer rates for a given heat exchanger area and temperature drop. Fouling of heat exchangers can occur if the stream has a corrosive composition. Advanced materials, filtering and regular maintenance can all limit this problem (US DOE 2008) but are not without additional expense.

[17] The latent heat is that released during the phase change of a system (in this case from gas to liquid). Conversely the sensible heat is the energy associated with the kinetic energy of molecules in a system and is the heat utilised in most conventional heat recovery applications.

6.1.2 Heat pumps

6.1.2.1 Vapour recompression heat pumps

Heat exchangers can be used when there is a heat demand below that of the heat source, they are used to channel the natural flow of heat from a higher to lower temperature. When there is a source of waste heat at a lower temperature than that required a heat pump may be used to increase the temperature of the waste heat source (Soroka 2011). This is illustrated in Fig. 6-2. High grade energy is input to increase the temperature of the heat available. The majority of heat pumps use mechanical drives for the high grade energy input, usually in the form of electric motors. These are known as vapour recompression heat pumps. The discussion in this section applies to this technology. Another form of heat pumps, where high temperature heat is used as the energy input are known as absorption heat pumps and are discussed in section 6.1.2.2 below.

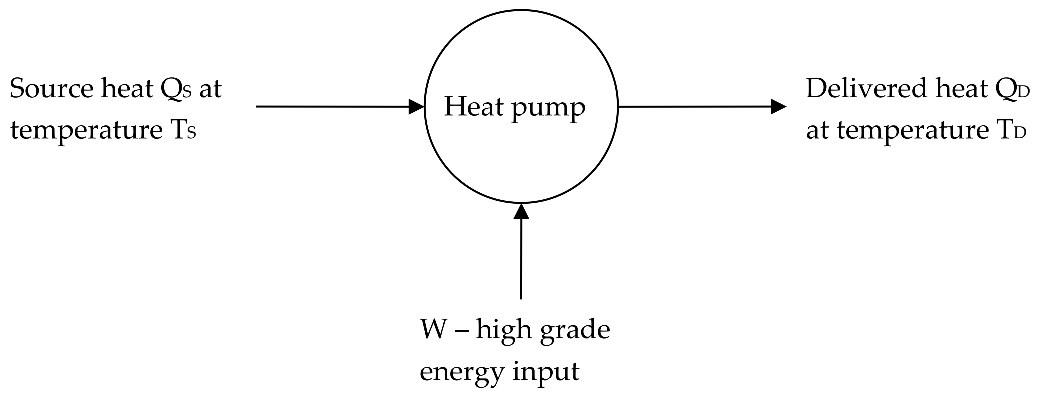

Fig. 6-2: Schematic of a heat pump, adapted from Soroka (2011).

The source of lower temperature heat can be the environment in the form of air, ground, or water sources or (within industry) waste heat. Waste heat has the advantage of being at a higher temperature than an air or ground source, so allowing higher temperature outputs or increased performance of the heat pump (see below). In addition the heat source is less likely to fluctuate seasonally as an air source does, a fluctuation of the heat source will limit performance. As heat pumps utilise heat from a 'free' source they output more thermal energy than the energy input to drive the process. The heat output (Q_D) is equal to the heat input (Q_S) plus the work input (W) assuming no losses (Hita et al. 2011). Heat pumps can therefore output more heat for a unit of energy demand than a conventional (boiler) system. Taking the inefficiencies of electricity generation into account (assuming a heat pump powered by an electric motor) heat pumps can use less primary energy than conventional systems, given sufficient operating conditions (US DOE 2008). If electricity generation becomes decarbonised heat pumps will also become increasingly attractive from an emissions perspective. The use of a heat pumps will have an additional investment cost over the alternative (usually steam based) heating system, but will have lower operating costs due to a lower energy demand (Hita et al. 2011).

The relevant characteristics that define the usefulness of a heat pump in a particular application are the temperatures at which the heat pump can receive and reject heat, the maximum temperature lift that is achievable, and the efficiency of the system (US DOE 2008). The performance of a heat pump is measured with the coefficient of performance (COP) which is the ratio of heat output (Q_D) to work input (W), so that:

$$COP = \frac{Q_D}{W} \tag{6-3}$$

The temperatures of the source and demand are important in defining the COP of the heat pump, the maximum theoretical COP (Carnot COP), is given by the following equation (Hita et al. 2011):

$$COP_{Carnot} = \frac{T_{D*}}{T_{D*} - T_{S*}} \tag{6-4}$$

T_{D*} and T_{S*} are the temperatures of the refrigerant used in the system, which are approximately 5°C different to the temperature of the source and demand temperatures (a temperature difference being required to drive heat transfer). $T_{D*} = T_D + 5$ and $T_{S*} = T_S - 5$. Equation (6-4) shows that as the temperature difference between the source and demand increases the COP lowers. The COP reached in practice is approximately 55% to 75% the Carnot COP (Hita et al. 2011, US DOE 2009).

The maximum temperature that can currently, technically be supplied by heat pumps (T_D) varies, being partly dependent on the technology used, but is between 100°C and 190°C , with the maximum temperature lift (T_D- T_S) being up to 90°C (IEA Heat Pump Centre 2011, Soroka 2011). Costs increase as the maximum temperature that can be supplied increases however. The cheapest heat pump designs being those that are derived from air conditioning and refrigeration systems (Hita et al. 2011). In practice current heat pumps are providing heat up to 80°C, with temperatures up to 140°C expected to reach market by 2015 (Hita et al. 2011). Higher temperature heat pumps would be expected to be commercialised at a later date.

6.1.2.2 Absorption heat pumps

In the majority of industrial applications a heat pump would be driven by a mechanical drive (usually an electric motor). The high grade energy input in Fig. 6-2 can also be high temperature heat however. There are two applications of this technology, high temperature heat can be used to upgrade low grade heat to a medium temperature. This is known as a type I absorption heat pump, or a heat amplifier (US DOE 2009). This type of heat pump is not commonly used in industry for heating applications (IEA Heat Pump Centre 2011). However it can be optimised so that the heat is extracted at a temperature that fulfils a chilling requirement (US DOE 2009). In this manner waste heat can be used to provide chilling in industry, this technology is known as absorption chilling. There are two widely available types of technology available, single effect units use heat at approximately 100°C to supply chilling with a COP of 0.7 (US DOE Industrial Technologies Program 2006a). Double effect units[18] use heat at 165-180°C to

[18] Double effect chillers use two condensers and generators in the cycle, rather than one as in single effect units. This allows higher efficiencies.

provide chilling with a COP of 1.0 (US DOE Industrial Technologies Program 2006a). This technology also outputs hot water (Horbaniuc 2004), that can be utilised if a demand exists. Another heat pump application is the type II absorption heat pump, or temperature amplifier (US DOE 2009). This takes a medium temperature heat source and outputs heat at both a higher and lower temperature, with virtually no external drive energy (IEA Heat Pump Centre 2011). This has a COP well below unity, typically 0.45 to 0.48 (US DOE 2009).

6.1.3 Heat-to-power

Another use of waste heat is in conversion to electrical power. There are generally greater inefficiencies and costs in converting heat to power, rather than using the heat in a more direct manner. However there are also significant advantages. When heat is converted to electricity it can fulfil a large range of demands, or easily be transported and sold to electricity suppliers if an immediate demand does not exist. The maximum amount of electrical power that can be extracted from a heat source is dependent on the temperature of the source and also the heat sink. The Carnot efficiency represents the maximum efficiency of power generation for a given heat source and sink (as discussed in Chapter 2). This is illustrated in section 6.2.5 below in comparison to the efficiency displayed by existing equipment. When there is a uniform sink temperature (usually the environment temperature) the higher the temperature of the heat source the greater proportion of it can be converted into electrical power.

The Rankine cycle is often used in conventional power generation (Boyle et al. 2003). The combustion of fuel produces heat, this heat is used to produce steam and the steam is used to power a turbine and produce electricity. In a similar manner a waste heat boiler can be used to convert surplus heat to power using the Rankine cycle. Waste heat is not usually available at the same temperatures and in the same quantity as the heat produced for conventional power generation, this can limit the use of the Rankine cycle. As the temperature of the heat source drops the traditional Rankine cycle becomes less cost-effective as lower pressure steam requires bulkier equipment (US DOE 2008). A lower temperature heat source will also not superheat the steam, this can cause condensation of the steam and erosion of the turbine blades. The organic Rankine cycle (ORC) works on the same principles as the Rankine cycle but uses an alternative working fluid to replace the water used in the conventional cycle. This fluid has a lower boiling point, this allows lower temperature heat sources to be utilised in power production. The fluids used in the ORC also have higher molecular mass than water. This allows compact designs, higher mass flow rates and more efficient turbines (US DOE 2008). There are a number of fluids that can be used in an ORC, the choice of which will vary depending on application (Chen et al. 2010, Nguyen et al. 2010). Alternative heat to power cycles that could potentially be used in industrial waste heat applications include the Kalina cycle (Ogriseck 2009), Stirling engine and Inverted Brayton cycle (Bianchi and De Pascale 2011). However these cycles are not as well established as the traditional and organic Rankine cycles, in waste heat to power applications. Of these alternatives the Kalina cycle shows the most potential. The Kalina cycle is based on the ORC with different working fluid and offers advantages if the heat source is prone to fluctuations. It also uses traditional, off-the-shelf, equipment used by the standard Rankine cycle and so has the potential for lower costs than the ORC (Cunningham and Chambers 2002). However it is technically more complex, less tested than the ORC and currently more capital intensive (Pehnt et al. 2011). There are additional technologies currently in the development stage that rather than utilising a thermodynamic cycle convert heat directly to electricity. These technologies include thermoelectric, thermionic, piezoelectric and thermo photo voltaic devices, they are however yet to be utilised in industrial waste heat applications and would currently be prohibitively expensive (US DOE 2008).

Temperature limits on the waste heat source are imposed by the technologies used. The minimum temperature of waste heat required for an ORC system can be as low as 66°C if appropriate working fluid is selected (US DOE 2008). However in practical applications a limit of 90°C is sensible (Handayani et al. 2011). There is also a maximum temperature for which heat can be used in the Rankine cycle. At high temperatures steam becomes highly corrosive and oxidises conventional steels very quickly (Boyle et al. 2003). Stainless steel may be used to allow temperatures up to 600°C to be used but this is expensive and using conventional materials temperatures are limited to approximately 550°C (Boyle et al. 2003). Air bleeding (see section 6.1.1) can be used if higher temperature sources are used. This limit on the temperature of the cycle limits the maximum efficiency that can be reached. In selecting a cycle to convert waste heat-to-power a general rule is that at higher temperatures the traditional Rankine cycle is used, whilst at lower temperatures an organic fluid is required. However other factors such as the composition and size of the heat source influence at what temperature one technology takes preference over the other. As an approximate measure water is generally used as the working fluid at temperatures above 400°C (Handayani et al. 2011, Pehnt et al. 2011, US DOE 2008). Below this temperature equipment becomes bulkier and less cost effective, there is also a danger of condensation and subsequent erosion of turbine blades (US DOE 2008). This is a generalisation however, there are instances of organic working fluid being used with a source temperature of approximately 500°C (Rossetti 2011, US DOE 2008).

6.1.4 Heat transport

It is possible to transport heat between locations so the recovery potential from one site can fulfil a demand at another. The most well established technology for this purpose, which is used in district heating networks, is via a pipeline utilising the sensible and/ or latent heat of water. District heating networks typically use hot water at 80-120°C, whilst higher temperatures can be supplied in industrial networks using steam at a few hundred degrees (DECC 2012h). There are a wide range of alternative technologies for transporting heat, that are in the development stage, and not known to currently be used in practice. These technologies are based on reversible chemical reactions, phase change thermal storage, or absorption and adsorption techniques (Ammar et al. 2011, Ma et al. 2009, Mazet et al. 2010). These alternative technologies may deliver advantages in terms of the economically feasible distance that heat can be transported, by limiting both the capital cost of infrastructure and losses associated with the use of a pipeline over longer distances. The possible temperature of heat transfer, in comparison to those using water based systems is also increased using these alternative technologies. As an example a chemical catalytic chemical reaction has the potential to absorb heat at about 950°C and release heat around 500°C (Ma et al. 2009).

The distance heat can feasibly be transported is limited by the costs of the transportation network and the losses of enthalpy and exergy encountered. This distance would be expected to vary considerably for different projects and a range of values are given in the literature. It is reported that using water or steam pipelines transportation is limited to 10km at 300°C (Ma et al. 2009). At lower temperatures as losses to the environment are less there are examples of a Swedish district heating network transporting heat at 120°C for 40km and a pipeline in Iceland carrying heat at 90°C for almost 70km (BERR 2008b). The efficiency of heat transportation is also open to considerable variation for individual projects. For this reason figures are not often quoted in literature. One study simulated efficiencies of heat transportation over 30km, efficiency with a hot water or steam based system was 32%, this increased to 53% using a chemical reaction based system using methanol, and 75% using a double stage methanol process (Ma et al. 2009).

6.2 METHODOLOGY

The technologies examined in estimating the heat recovery potential in UK industry were chosen as:

- On-site heat recovery using heat exchangers
- Upgrading of heat sources using heat pumps
- Providing chilling using absorption heat pumps
- Generating electrical power using Rankine and ORC cycles
- Transporting heat for use at other industrial sites.

These were felt to be the most likely used technologies in waste heat recovery. The following section explains how the potential for using each of the technologies was estimated based on the database of industrial heat demands and recovery potentials. The analysis here was undertaken using Visual Basic programming within Microsoft Excel. There are two methods in which each opportunity was assessed. Firstly the potential for using each technology if all the waste heat identified was available for use with the specified technology and secondly if the heat available for a particular technology was limited by the use of the heat first by more attractive technologies. A hierarchy was applied to the second case so the most economically attractive technologies are prioritised in utilising the waste heat source. This is detailed in section 6.2.7. The technical potential for the various forms of heat recovery was estimated here, whilst economic, and other issues were considered in the choice of parameters used in the calculations, the costs of the different options were not explicitly assessed.

Temporal restrictions were ignored in this analysis, this would likely be most important when transporting heat between sites. The load factors of the sites examined were estimated based on the subsector in which they operated (Hammond and Norman 2010). The calculations undertaken were generally based on the power of heat recovery, this therefore takes into account the different load factors of sites but not their operating schedules. Results were presented in energy recovered per year as this was felt to give a more easily understood and comparable measure than power. Where there is sharing between sites the lower load factor of the site was used in converting power to energy.

6.2.1 Dataset

For each site in the NAP of the EU ETS (supplemented with additional information on large energy users) information on location, heat demand, and estimated heat recovery potential was available from previous work, see Chapter 3, McKenna (2009) and McKenna and Norman (2010). For each site, based on emissions or output data and the classification of the site into one of 33 subsectors, heat demand was estimated in five temperature bands (less than 100°C, 100-500°C, 500-1000°C, 1000-1500°C and over 1500°C) and the heat recovery potential was estimated (at a single temperature). A range was applied to the quantity of energy available as waste heat, representing the uncertainty in this value. The heat recoverable was estimated as a conservative technical potential, not the total waste heat arising, therefore it was assumed that this potential was available as an output from a heat exchanger, or as an input to other heat recovery technologies. The heat recoverable only included the sensible heat component. For the current work any heat demand currently fulfilled by CHP plants was removed. This demand was already met in an energy efficient manner, and so it was not felt appropriate to replace it with surplus heat. There were 425 sites included in the analysis, after discounting the sites include in the NAP that were solely supplied by CHP. The data used refers to the situation from 2000-2003 with heat demand and recovery potential based on the mean emissions recorded in these years with the highest and lowest figures removed. Chapter 3 explains changes expected to the data since this time period and the methodology in its construction.

6.2.2 On site-heat recovery

For each site in the analysis if there was a heat demand in a temperature band below the temperature of the surplus heat than heat recovery was assumed to be possible. All, or part, of the surplus heat could be recovered in this manner, dependent on the size of the demand. Sites that were classified separately in this analysis as they undertake different processes, could exist at the same location. The most significant example of this was the integrated Iron and steel sites, where different parts of the steel making process were classified as different sites, but were at the same location. Using waste heat at another site, but at the same location was included within heat reuse-on-site in this work. Reusing heat at the same site (rather than same location) was prioritised however, as there were likely to be additional temporal and spatial constraints if sharing between different sites. If multiple heat demands existed that could be filled by the recovery potential the highest temperature demand was prioritised, maximising the exergy efficiency of the heat transfer process. There may be some additional energy requirement for heat recovery associated with pumps and control systems required as part of the heat recovery system. This would be small in comparison to the heat recovered however (Pehnt et al. 2011) and was ignored in this analysis. What was not accounted for by this analysis was the use of surplus heat for preheating combustion air or product to a temperature below that specified by the demand temperature. It was not possible with the data available to estimate this potential. This is discussed further in section 6.4 below. Limitations on the temperatures that could be recovered on-site using heat exchangers were not imposed. As discussed in section 6.1.1 there are often temperature limits imposed by economic and technical factors, on both lower and higher temperature ranges. There was also no limitation on the magnitude of heat recovered. The effects such limitations are likely to have are discussed later in the chapter in the context of the results.

6.2.3 Upgrading heat

Given the temperature limitations of current heat pumps (see section 6.1.2) the analysis limited the use of heat pumps to supply a heat demand in the lowest temperature band (less than 100°C) using a heat source within the same band. The performance of the heat pump is defined by equations (6-3) and (6-4) with a 5°C temperature difference between the refrigerant temperatures and the source and demand temperatures, and the real COP being 55% of the theoretical COP. If a surplus heat source existed at less than 80°C the possibility of using a heat pump was investigated and the COP calculated to determine the heat output and electricity input required for each site. This was found to represent a very small potential in the current analysis and no minimum equipment size was used to constrain the results.

6.2.4 Converting heat to fulfil a cooling requirement

The potential for utilising waste heat to fulfil a cooling requirement was estimated using absorption chillers (type I absorption heat pumps). The minimum output from commercially available units is around 350kW of chilling capacity (US DOE Industrial Technologies Program 2006a). Within UK manufacturing almost all the chilling requirement is within the Food and drink and Chemicals subsectors (DECC 2010d). For these subsectors the amount of chilling that could be provided using the surplus heat available was estimated. At waste heat temperatures of 100-170°C a single effect unit was assumed to be used with a COP of 0.7, at temperatures above 170°C a double effect unit would be utilised with a COP of 1.0. Although there is not a technical limitation on using higher temperatures (air bleeding could be used) when looking at combinations of technologies it may be sensible to impose a temperature limit on the heat sources used in absorption chilling. Results are therefore shown for two cases with no upper temperature limit enforced on absorption chilling, and with a limit of 300°C imposed. The 300°C limit was based on the author's own judgement. The upper temperature limit scenario was used when assessing the opportunities through a range of technologies. There may also be a hot water supply available when an absorption chiller is used. The additional potential savings through utilising this hot water were not examined here.

6.2.5 Electrical power generation

For the current analysis it was assumed that traditional and organic Rankine cycles could be utilised for converting heat-to-power. These are currently the most widely used technologies. Fig. 6-3 shows the Carnot efficiency of heat–to-power cycles with an environment temperature of 25°C. Also shown are the net efficiencies at different temperatures reported by four manufacturers of ORC systems (Gerson 2011, Rossetti 2011, Simcock 2011, Thornley and Walsh 2010) and a typical efficiency of a steam Rankine cycle at 550°C (Boyle et al. 2003). A logarithmic curve was fit to this data to estimate the efficiency of a heat-to-power cycle at a given temperature.

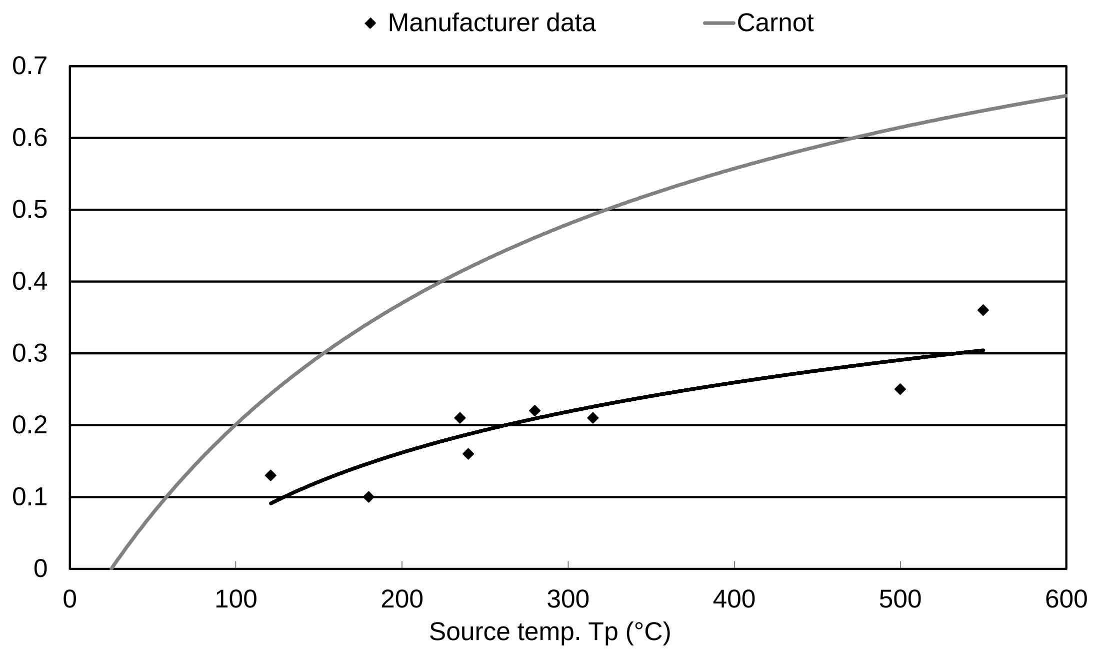

Fig. 6-3: Theoretical and practical first law efficiencies of heat-to-power cycles.

In the current study whether water or an organic fluid would be used in the Rankine cycle was not specified. The expected efficiency of a technology was based on the trend line shown in Fig. 6-3 and varied with the temperature of the surplus heat, rather than the technology used. The minimum power output for a viable heat-to-power project was set at 0.5MW. This was based on information obtained from manufacturers of ORC systems (Gerson 2011, Rossetti 2011, Simcock 2011). This required output was combined with information on efficiency to define the required power of waste heat at a given temperature. The lower temperature limit for heat-to-power application was set at 100°C. Information from manufacturers indicated a limit of 120°C (Gerson 2011, Rossetti 2011, Simcock 2011), although practical applications have been reported at 90°C (see section 6.1.3). The maximum temperature for which heat can be used was set at 550°C, this allowed conventional materials to be used in the equipment. At higher temperatures air bleeding could be utilised, so higher waste heat temperatures could be used, but the efficiency that could be reached was limited.

6.2.6 Use between industrial sites

The potential for transporting heat from one industrial site for use on another was estimated. Due to the uncertainties regarding heat transportation possible transportation distances between five and forty kilometres were examined. The efficiency of this heat transportation was assumed to be 25-75%, in reality this would likely be related to the distance heat was transported and the temperatures involved, however sufficient information on heat transportation efficiencies, to enable this approach, was not found. The range of efficiencies was therefore applied to each opportunity for heat transport to supply an indicative assessment. No restriction was put on the temperatures or magnitude of waste heat sources that could be recovered, these were examined in the context of the results, as for recovery on-site. Similarly to recovery on-site surplus heat was used to fulfil a heat demand in a lower temperature band. For use between sites to occur a site must exist within the distance specified by the analysis and have a heat demand in a lower temperature band than that of the recovered heat.

There may be multiple options for reusing heat at another industrial site. As the programmes used for the numerical analysis carried out calculations in the order which the data was presented the data was put into descending order based on heat recovery potential. Therefore if there was a situation where demand could be fulfilled by multiple recovery potentials the recovery potential representing the greatest amount of energy was prioritised. This approach does not guarantee an optimisation of the use of heat recovery, but should be sufficient for the aims of the current work, in providing an indicative assessment.

6.2.7 Combining the options for reusing heat

The heat recovery options presented above vary in the likely capital cost of a project to utilise the waste heat. Capital cost is expected to be one of the greatest barriers to the application of the heat recovery options (see Chapter 4 for a discussion of barriers to energy efficiency projects and section 6.4.7 below). The analysis therefore considered two cases for each technology. Firstly when all the identified recovery potential was available for use with the given technology. Secondly when the heat available was limited by more attractive technologies (with lower capital costs) having already had the opportunity to utilise the waste heat. Law et al. (2011), and similarly Handayani et al. (2011) suggest a hierarchy based on capital costs::

1. Direct use of heat (only requiring piping/ ducting, usually within the same process).
2. Onsite heat transfer using a heat exchanger.
3. Provide chilling using an absorption chiller, for use on-site.
4. Upgrade the heat, for use on-site, using a heat pump.
5. Generating electricity.
6. Export heat for use off-site.

This hierarchy is applied to the results here, options 1 and 2 are combined as the method of reuse on site was not specified.

6.3 RESULTS

6.3.1 The identified potential

Fig. 6-4 shows the annual heat demand split by temperature band and subsector for the 425 sites involved in the current analysis. This excludes heat demand currently fulfilled by CHP systems. The total heat demand represented here is 503PJ.

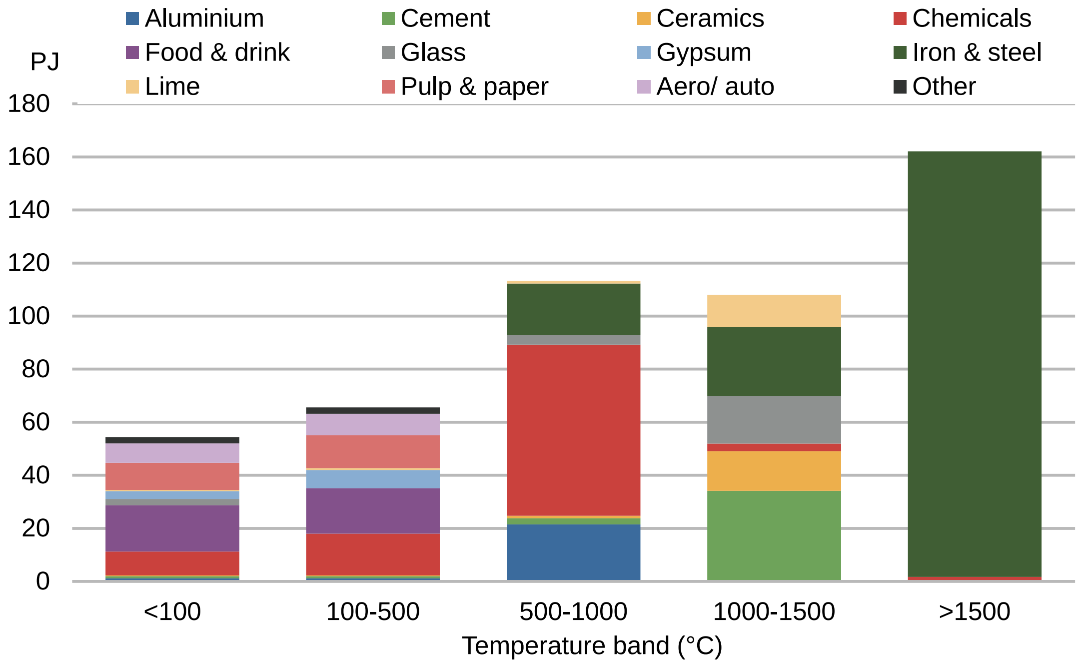

Fig. 6-4: Annual UK heat demand, by subsector and temperature band, excluding demand supplied by CHP.

Fig. 6-5 shows the annual heat recovery potential identified, similarly to Fig. 6-4 it is split by temperature demand and subsector. Due to the uncertainty surrounding the recovery potential a range was adopted in defining the waste heat available. The recovery potential shown in Fig. 6-5 represents the mean of this range. The total surplus heat available was 37-73PJ. The temperature bands shown for the recovery potentials are better defined than those for demand. There is uncertainty surrounding both areas, the temperatures are better defined for recovery potential as a conservative estimate of the temperature available was used. There is likely a range of temperatures available from different sites, with the results shown here representing the lower end of this range. In the assessment of the heat recovery options well-defined temperatures were required.

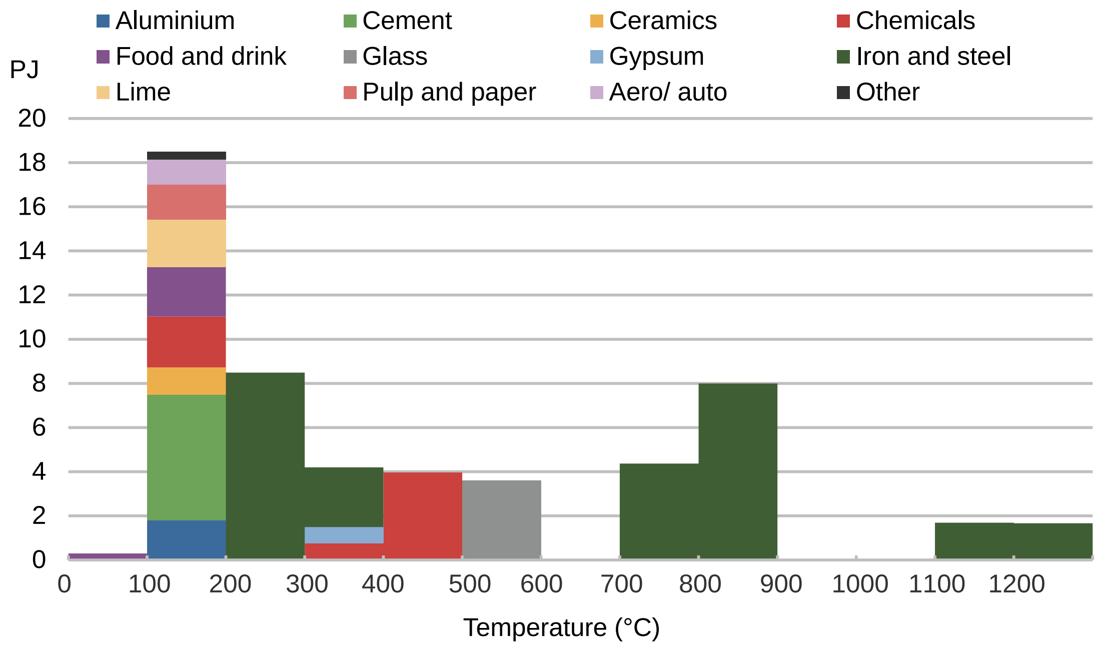

Fig. 6-5: Annual UK heat recovery potential identified, by subsector and temperature. Mean results shown.

Fig. 6-6 shows the annual heat recovery potential per site by subsector. The Iron and steel subsector is not shown, it was a heat recovery potential per site of 1500-3000TJ/site/yr. This indicates the large potentials of the Iron and steel subsector for heat recovery, especially given that the different operations of the integrated sites are classed as different sites in this analysis but are at the same location. The error bars in Fig. 6-6 represent the range of heat recovery potential estimated.

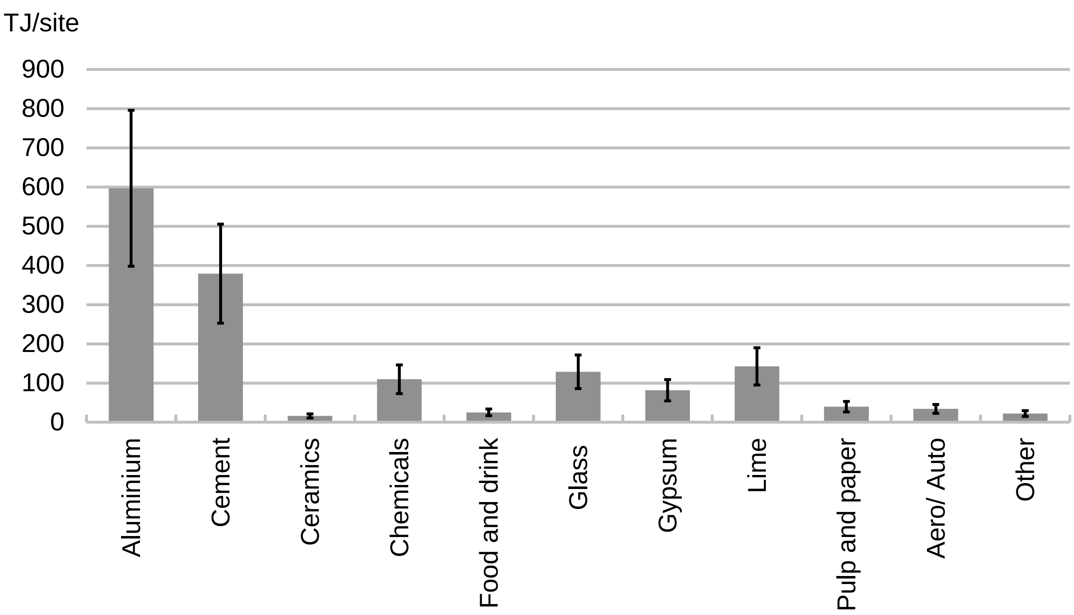

Fig. 6-6: Annual identified heat recovery potential per site, by subsector.

Fig. 6-7 shows the heat recovery and maximum work potential of the waste heat, or exergy (using the Carnot efficiency and a sink temperature of 25°C). The work potential is relatively greater in comparison to the energy of heat recoverable when the waste heat is available at a higher temperature. The total exergy available is 27PJ at the mean estimate, therefore representing approximately half the energy recoverable of 55PJ.

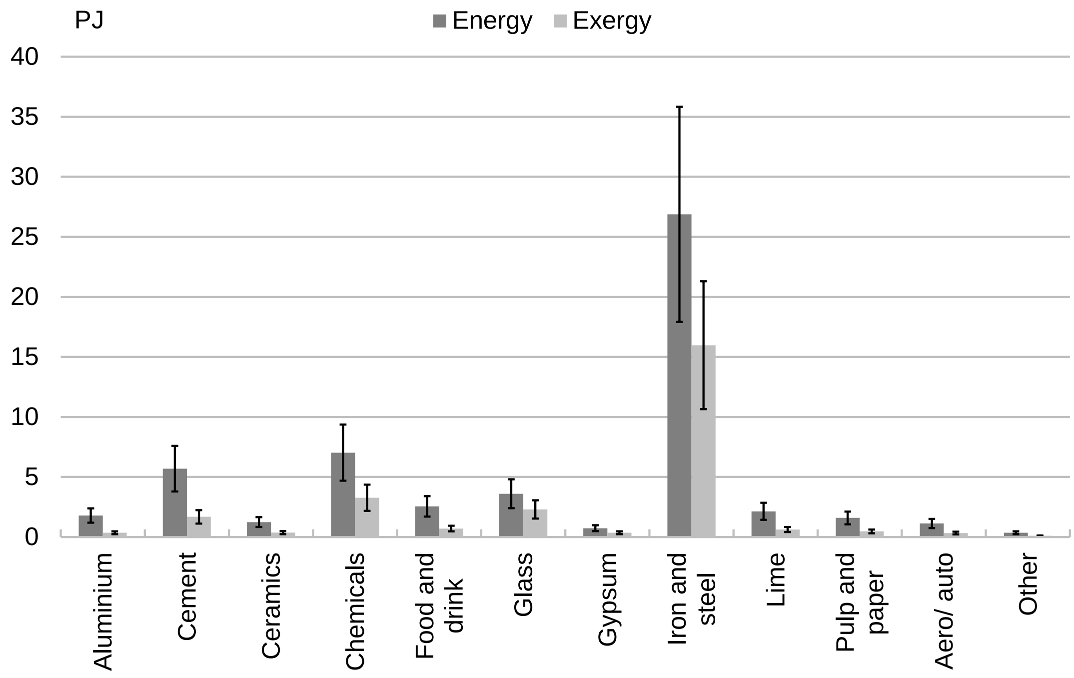

Fig. 6-7: Annual heat recovery available in each subsector and exergy of the heat.

Fig. 6-8 shows the cumulative heat recovery potential when the sites are ordered in terms of the magnitude of heat recovery potential. It is clear that the majority of heat recovery potential lies in a relatively small number of sites.

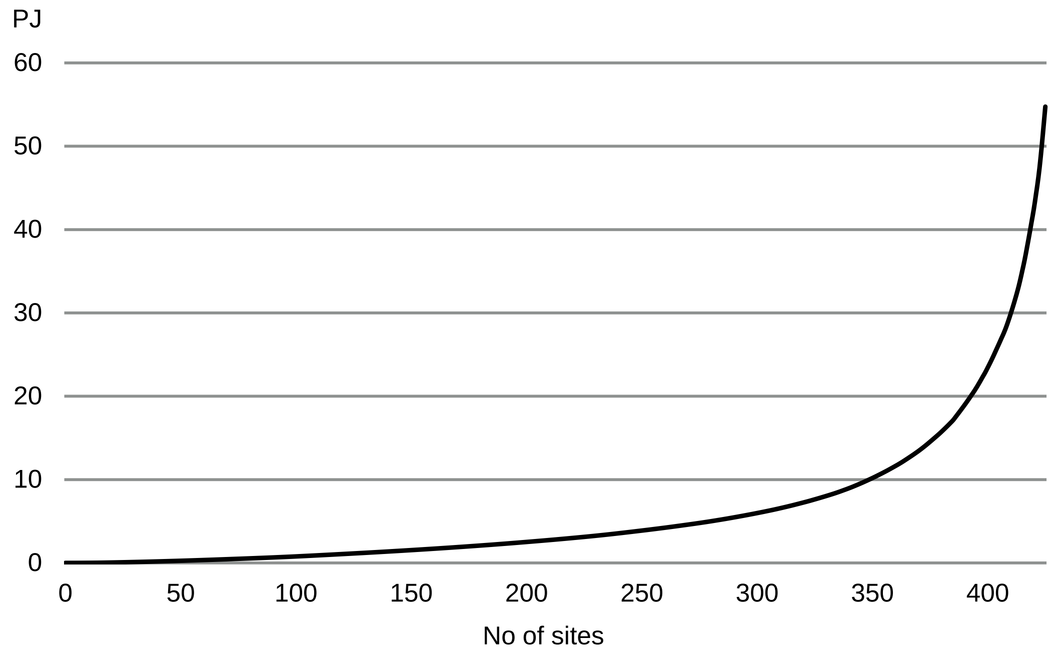

Fig. 6-8: Cumulative annual heat recovery potential by number of sites.

6.3.2 Onsite heat recovery

Fig. 6-9 shows the results of the analysis for the annual on-site heat recovery potential by subsector. Error bars represent the range in the results when using the minimum and maximum estimations of heat recovery potential. The small range shown for some subsectors indicates recovery on-site is limited by the existence of a suitable demand rather than the availability of surplus heat. The total amount of surplus heat that can be reused on-site is 15-23PJ/yr.

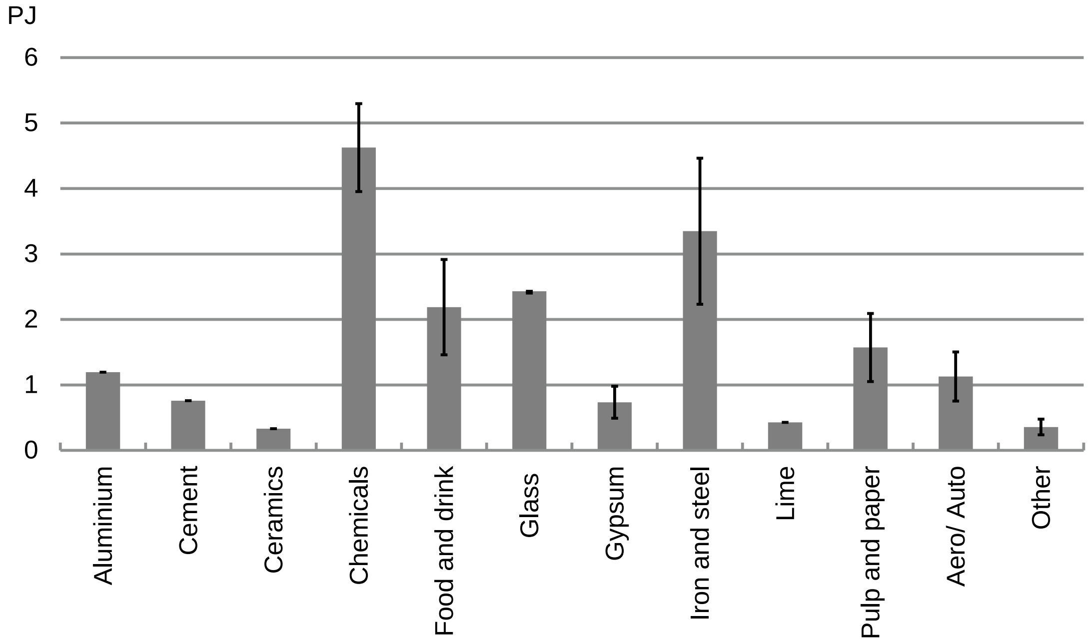

Fig. 6-9: Annual on-site heat recovery by subsector.

For each subsector Fig. 6-10 shows the proportion of subsector heat recovery potential that could be used for on-site recovery and the proportion of sites in each subsector that are able to use on-site recovery. The results for the mean heat recovery potential are shown. It can be seen that the proportion of sites at which on-site recovery occurs is greater than the proportion of heat recovery potential recovered on-site. This indicates that there are many sites for which recovery on-site is possible but the heat demand is not large enough to utilise the entire recovery potential. Reusing only part of the recovery potential would likely not be as economic as being able to reuse the full potential. For the industrial sector as a whole 35% of the heat recovery potential can be used with on-site recovery, with recovery occurring at 92% of sites (both these values are for the mean heat recovery). The low amount of recovery within certain subsectors with a high resource of surplus heat (mainly Iron and steel, but also Cement) limits the overall recovery seen.

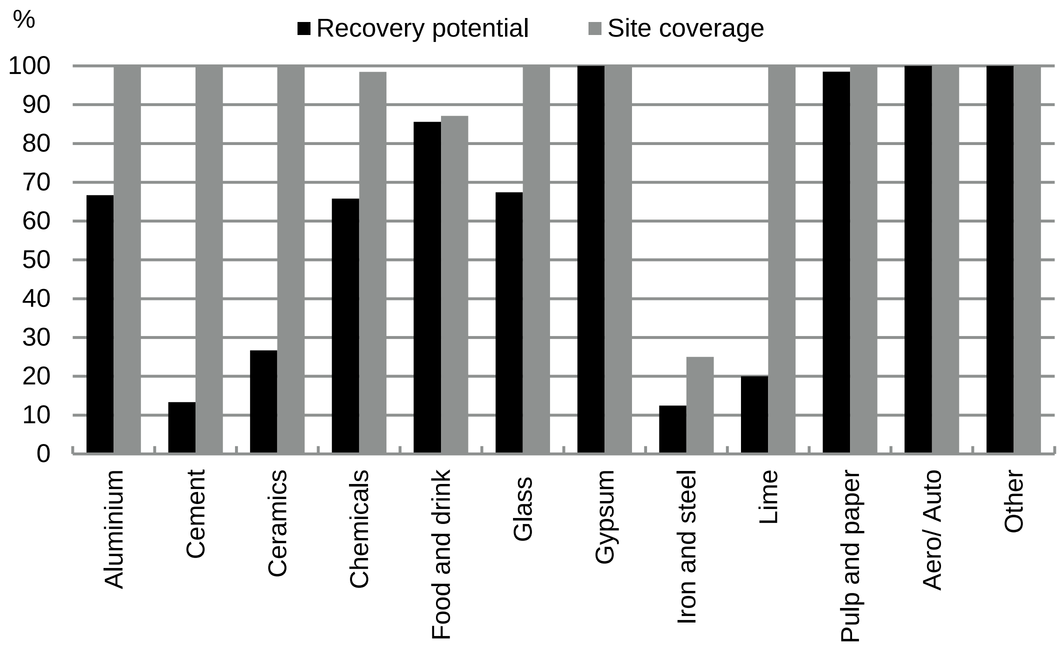

Fig. 6-10: Proportion of subsector recovery potential realised with on-site recovery and proportion of subsector sites at which on-site recovery is possible.

Fig. 6-11 shows the mean recovery potential per site for the different subsectors investigated. The mean results are shown.

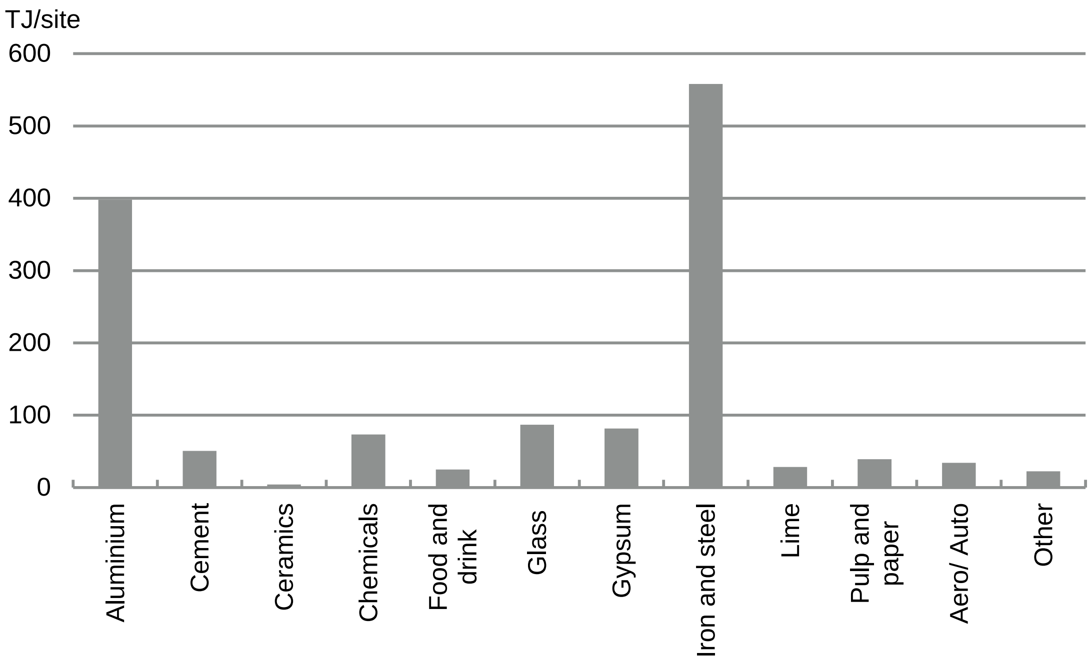

Fig. 6-11: Annual on-site recovery potential per site by subsector.

Fig. 6-12 and Fig. 6-13 show the temperature bands of heat recovery and use respectively. The majority of recovery potential is to fill a demand in the less than 100°C temperature band. The temperatures of heat recovery (see Fig. 6-5 for all recovery available) are on the whole too low to fulfil demand in other temperature bands. This <100°C temperature band has the smallest demand of any of the temperature bands (see

Fig. 6-4), limiting recovery on-site. Additionally heat recovery in this temperature range is costly, due to the potential for corrosion of the heat exchangers. The Iron and steel sector shows potential for recovery at higher temperature bands, with recovery from the 1000-1500°C temperature band to fulfil a demand in the 500-1000°C band identified in the current analysis. Again however this may require advanced materials in the heat exchangers to reuse heat as this high temperature. The most viable temperature for heat recovery is fulfilling a demand in the 100-500°C temperature band. The only example of this in the current analysis is the recovery of heat from a Glass manufacturing site to be reused at a Cement site at the same location. This is very small compared to total potential (see Fig. 6-13). That there is little potential for heat recovery to this temperature band suggests opportunities to do so have already been realised as this is usually the most economic form of heat recovery.

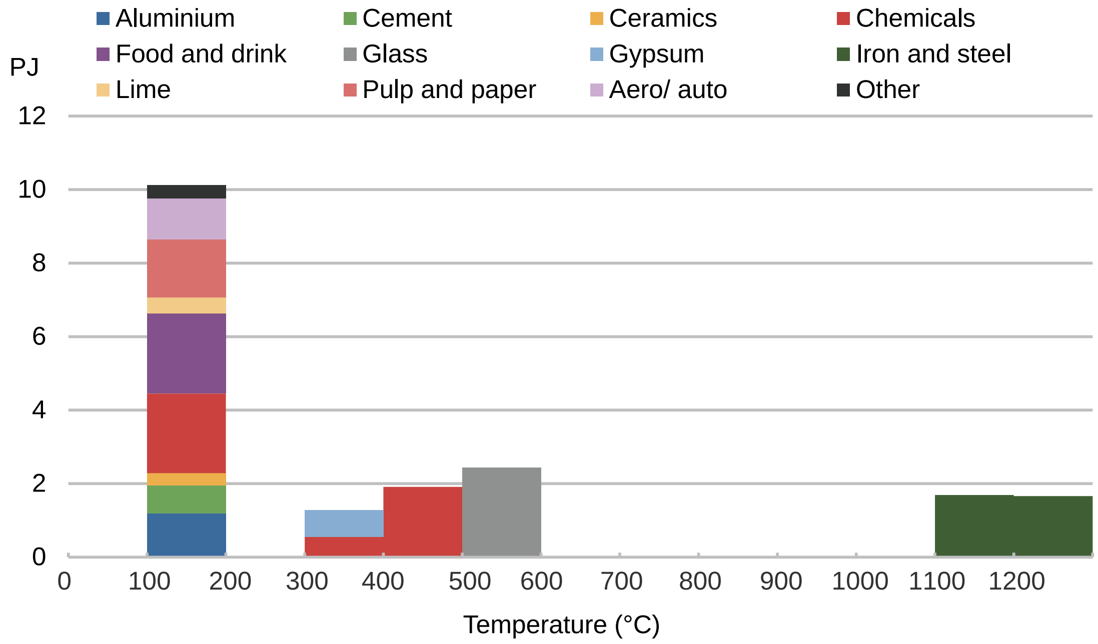

Fig. 6-12: Annual on-site recovery potential. Subsector and temperature band of source.

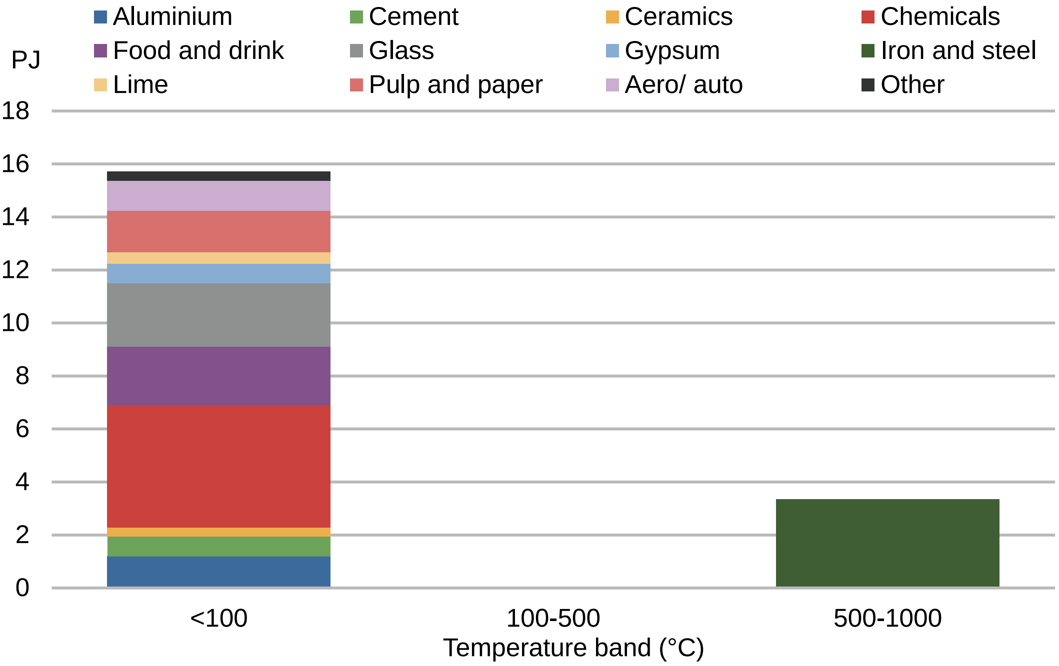

Fig. 6-13: Annual on-site recovery potential. Subsector and temperature band of sink.

Fig. 6-14 shows the power of heat recovery per site against the number of sites at which heat recovery at this magnitude occurs. It can be seen that at low powers, where recovery is likely the least economic there are a large number of sites. There are twelve sites with potential to recover >7MW of heat and not shown in Fig. 6-14. Of 393 sites where on-site recovery potential is identified half the sites contribute less than 10% of the total on-site heat recovery potential. The thirty sites with greatest on-site recovery potential comprise half the total recovery potential. This indicates the domination of a small number of sites in the recovery potential.

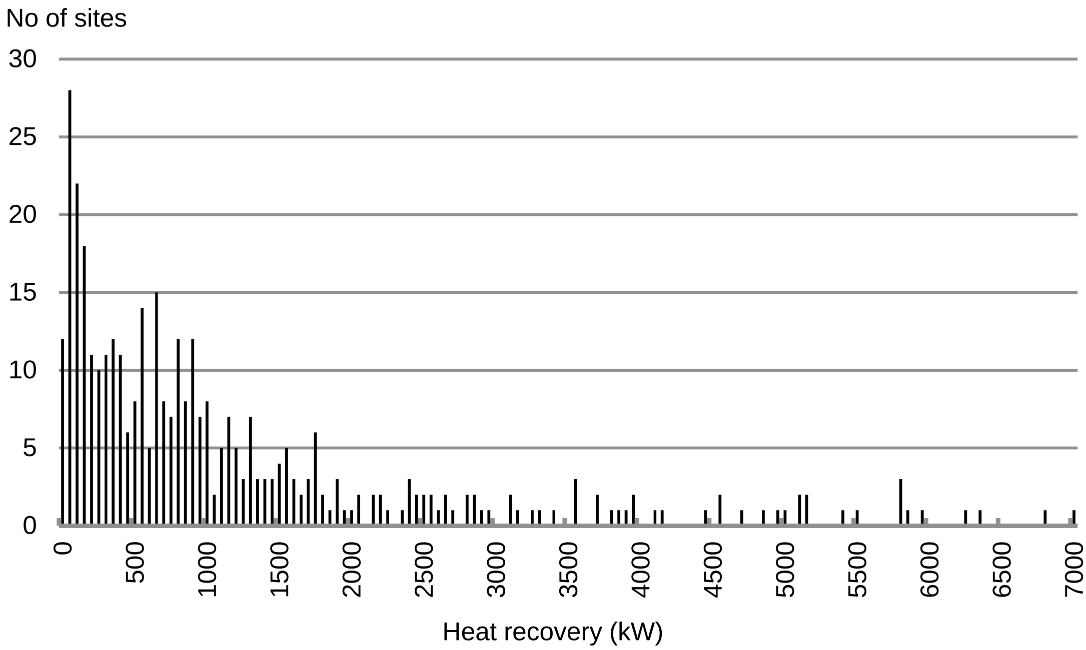

Fig. 6-14: Number of sites recovering heat on-site against the power of recovered.

6.3.3 Heat pumps

There are two subsectors in the analysis that have a heat recovery potential at less than 100°C and so may be suitable for utilising heat pumps. These are the Malting and Distilleries subsectors of Food and drink. The Distilleries subsector has a recovery potential at 80°C so was not considered suitable for current heat pump technology. In the Malting subsector heat recovery potential was at 40°C, and a large demand exists in the 0-100°C temperature band. Malting requires large amounts of air at 62-85°C (US DOE Industrial Technologies Program 2006b). Assuming a mean delivery temperature of 75°C gives a COP of 4.3 for a heat pump in this application. The heat that could be delivered at the three Malting sites, using heat pumps, is therefore 54-109TJ/yr. The individual heat pumps could deliver 0.5-2.1MW_{th} of heat. The heat that could be supplied in this manner represents 6-12% of the total site heat demand. There would also be an electricity demand for the heat pumps of 0.23kW_e per kW_{th} of heat supplied.

6.3.4 Absorption chilling

Fig. 6-15 shows the possibility for using absorption chillers to recover waste heat, with no upper limit on the temperature that can be utilised in this manner. In Food and drink where the heat is generally available at a lower temperature single effect chillers are the dominant technology, whereas in the Chemicals subsector where higher temperature waste heat is available double effect chillers are in the majority. This leads to a higher efficiency of converting waste heat to chilling capacity in the Chemicals subsector (overall COP of 0.9, compared to 0.7 in Food and drink). In total 5.6-12.2PJ of surplus heat was identified as the annual potential for reuse in absorption chillers, this could supply 4.9-10.4PJ of chilling capacity annually. According to the analysis the proportion of total surplus heat that could be reused with absorption chilling technology is 82% in Food and drink and 98% in Chemicals. The proportion of sites at which this technology can be used is 66% in Food and drink and 80% in Chemicals.

A supplementary analysis was undertaken with an upper temperature limit of waste heat used in absorption chillers of 300°C, as detailed in the methodology. The results are shown in Fig. 6-16 below. Here a potential to recover 2.5-5.9PJ/yr of surplus heat to supply 1.7-2.4PJ of chilling capacity was identified. Due to the reduction in higher temperature use the efficiency in converting surplus heat to chilling energy has been reduced. The proportion of waste heat that can be recovered in this manner is 82% in the Food and drink subsector and 31% in the Chemicals subsector. Such recovery occurs at 66% of sites in the Food and drink subsector, and 67% in the Chemicals subsector. Although the Food and drink subsector retains the same potential with an upper temperature limit the potential within the Chemicals subsector has been cut considerably. This lost potential was composed of eight sites, three of which composed the majority of the lost potential, having over 50MW_{th} of heat recoverable. The case with the upper temperature limit imposed perhaps forms a more realistic picture of potential. The sites with large heat recovery potentials that are excluded with an upper temperature limit would require correspondingly large chilling requirements to use absorption chilling systems.

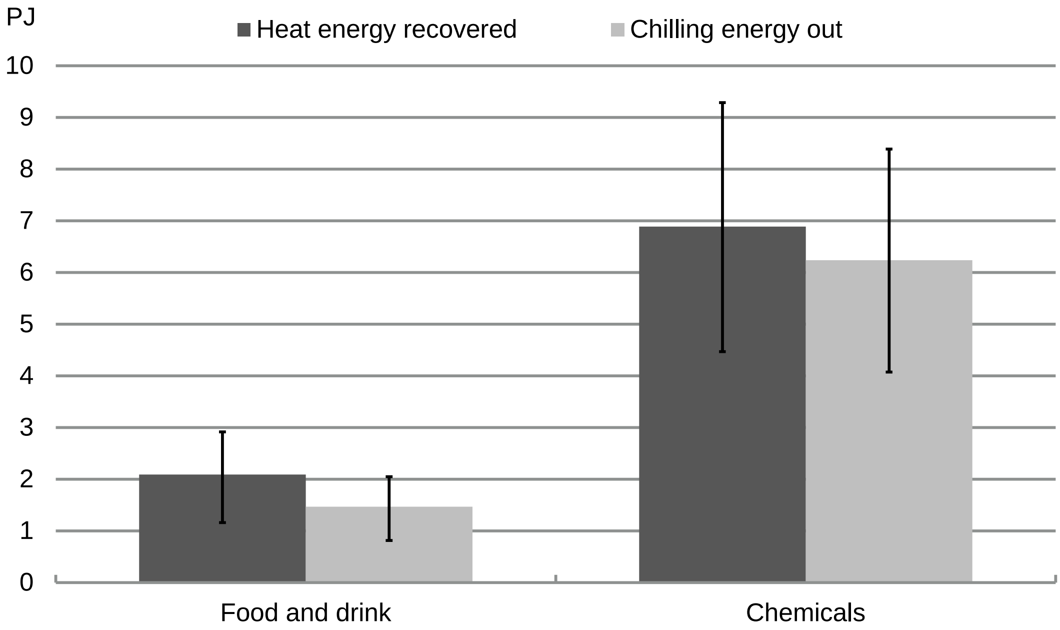

Fig. 6-15: Annual heat energy recovered and chilling energy supplied with absorption chillers.

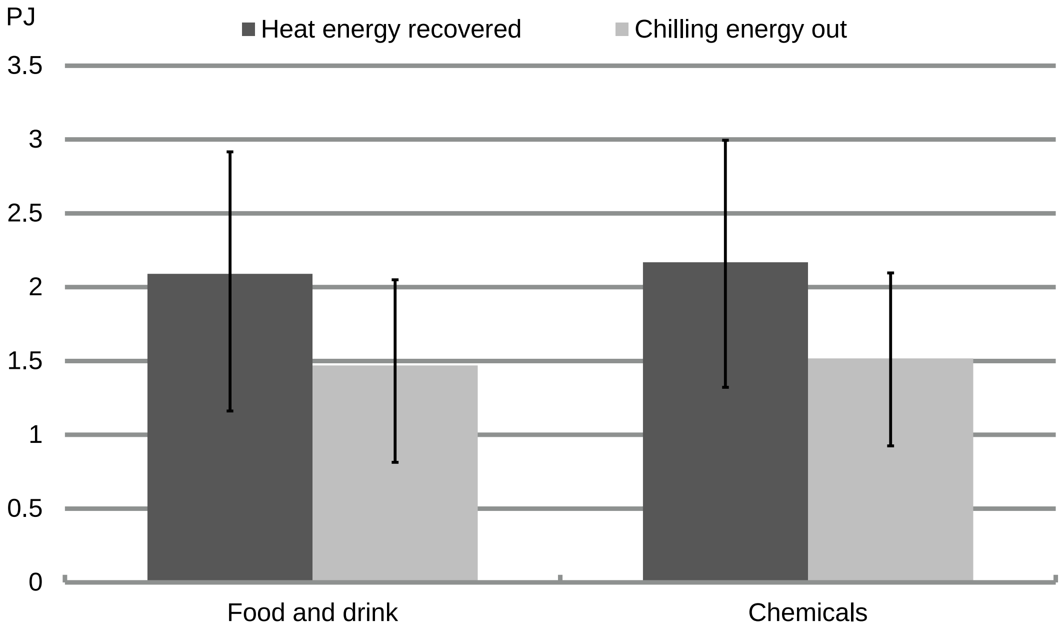

Fig. 6-16: Annual heat energy recovered and chilling energy supplied with absorption chillers, with upper temperature limit of 300°C.

6.3.5 Heat-to-power

The heat used and electrical energy output utilising heat-to-power technologies are shown in Fig. 6-17. The Iron and steel sector is not shown in Fig. 6-17 as it dominates the output. It is estimated Iron and steel could recover 17.9-35.8PJ/yr of heat energy to supply 4.5-9.0PJ/yr of electricity. In total 29-64PJ/yr of heat, supplying 6.7-14.0PJ/yr of electricity was identified for use in heat-to-power technologies.

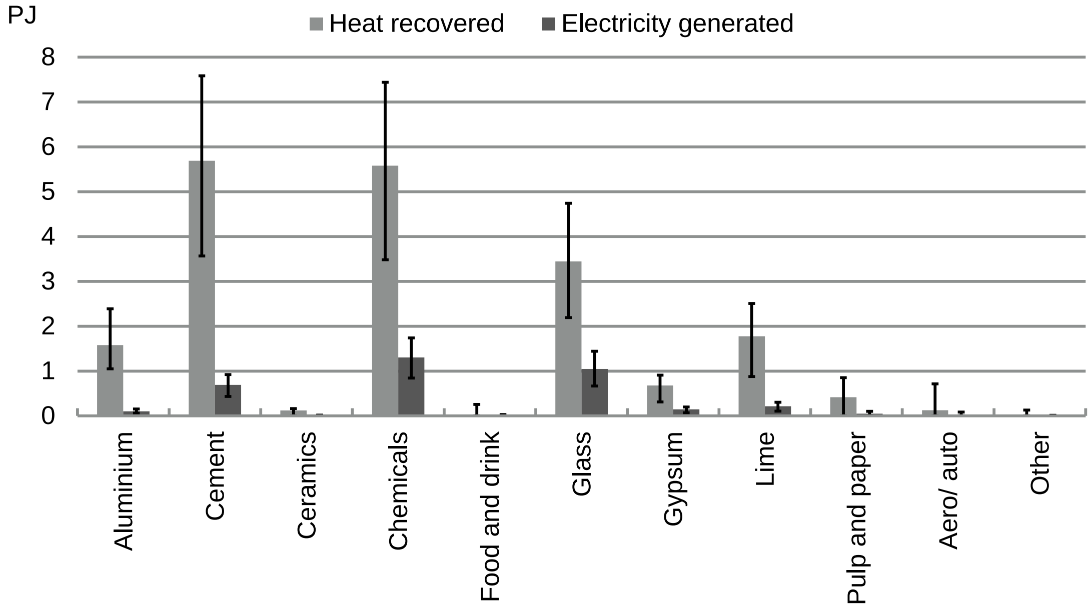

Fig. 6-17: Annual heat recovered and electrical energy output from heat-to-power technologies.

Fig. 6-18 shows the proportion of total surplus heat recovered through heat-to-power technologies and the proportion of sites at which this is possible. The results shown are for the case of the mean heat recovery potential. There is little potential in those subsectors with a low amount of surplus heat per site, this is especially so where the temperature of surplus heat is also low, limiting the efficiency of heat-to-power conversion. In these cases it is not possible to generate more than 0.5MW of electricity, the minimum required output in this analysis. 80-87% of total surplus heat is available to be converted to power but at only 18-26% of sites. This reaffirms the domination of a small number of sites in the overall heat recovery potential. Out of ninety-five sites with heat-to-power recovery possible, twelve make up over half of the electrical power output.

Fig. 6-19 shows the temperature from which heat is recovered for conversion to power. The domination of the Iron and steel sector can be seen here, especially at higher temperatures, leading to higher conversion efficiency of heat-to-power (Although no advantage is gained for any temperature over 550°C, see section 6.2.5).

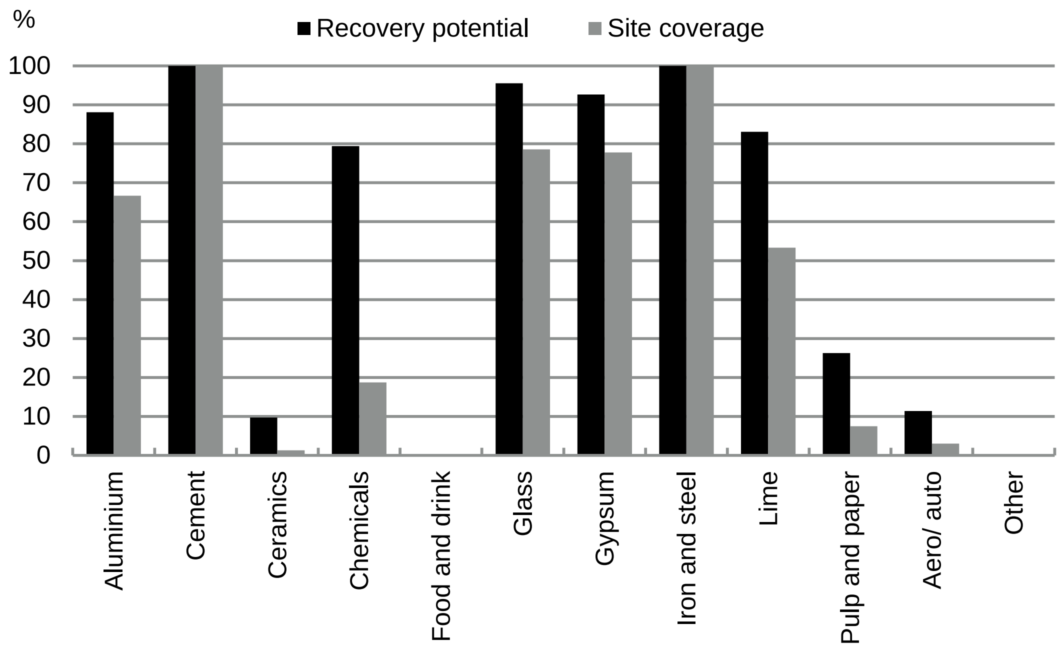

Fig. 6-18: Proportion of total recovery potential realised with heat-to-power recovery and proportion of sites at which this is possible.

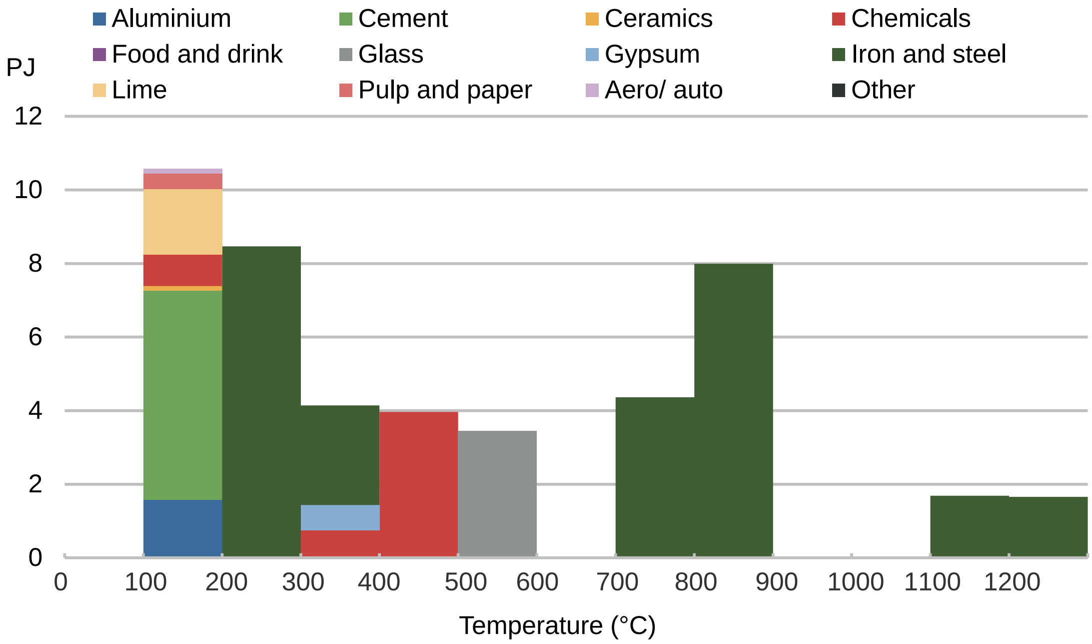

Fig. 6-19: Heat recovered for conversion to power, split by temperature band and subsector.

6.3.6 Heat transportation

Fig. 6-20 shows the potential for transporting surplus heat between industrial sites as the distance that it is possible to transfer the heat varies. The error bars are formed from a combination of the range of available surplus heat and the efficiency of the heat transport process (25-75%). The points represent the case of mean surplus heat availability and 50% transportation efficiency. Fig. 6-20 shows what would be available to the user of the heat, rather than the heat recovered at the original site.

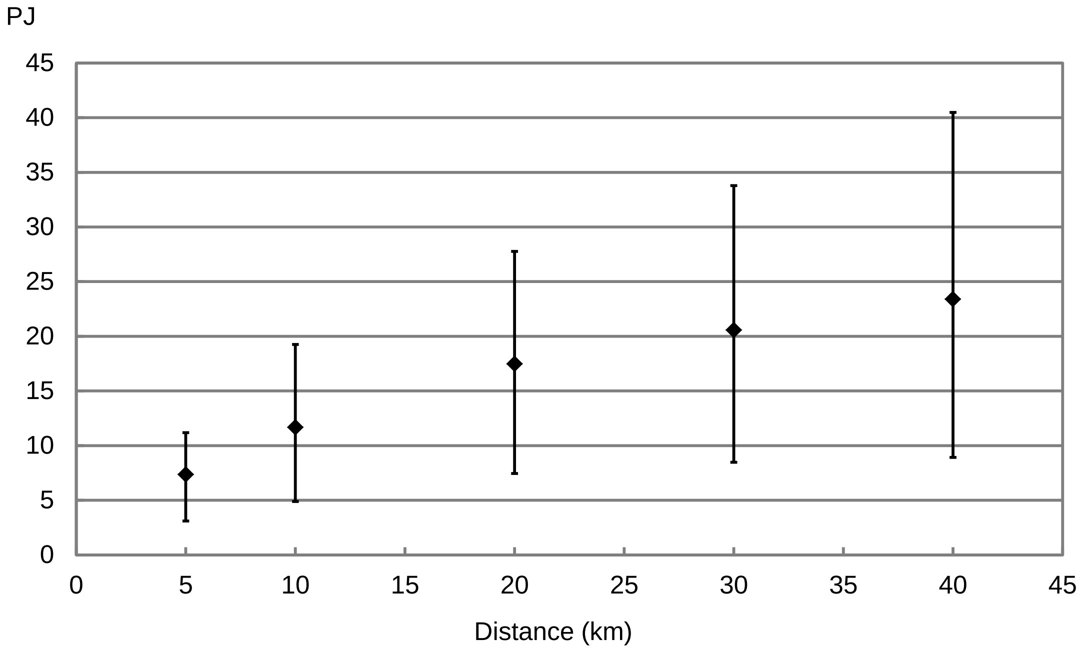

Fig. 6-20: Annual recovery potential by transporting heat as distance varies.

Fig. 6-21 and Fig. 6-22 show the subsectors and temperature bands that heat is recovered from and to, with a possible transportation distance of 10km, and an efficiency of 50%. Approximately 70% of the potential is for recovery in the lowest temperature band (less than 100°C) and so could be recovered with currently available water based transportation systems, but may also face problems of condensation and corrosion at the heat exchanger on the source site. Approximately 25% of potential can be recovered in the 100-500°C temperature band, with the remaining 5% in the 500-1000°C temperature band. Steam based transportation systems may be suitable for transporting heat in the 100-500°C temperature band, whilst above this it may be difficult to transport this heat with current technology. Increased potential for reusing heat in the 100-500°C range is seen compared to when heat can only be reused on-site.

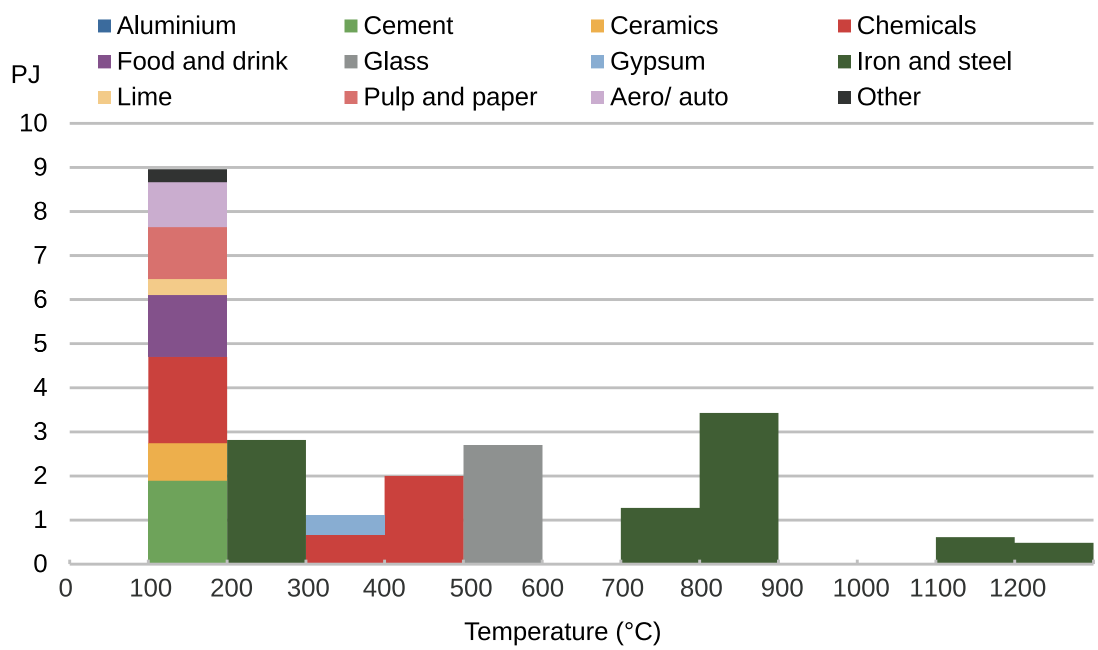

Fig. 6-21: Annual heat recovery for transportation, source temperatures and subsectors shown for 10km transportation distance.

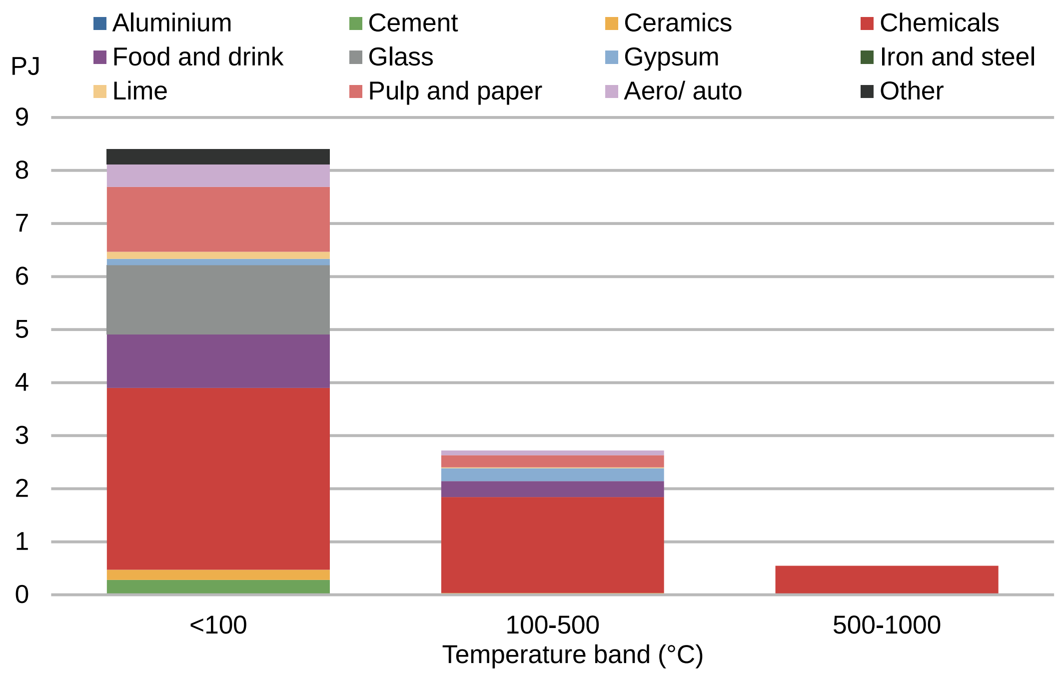

Fig. 6-22: Annual heat recovery for transportation, sink temperatures and subsectors shown for 10km transportation distance and 50% efficiency.

With a transportation distance of 10km and an efficiency of 50% 23.4PJ/yr of heat can be recovered from 280 sites to supply 11.7PJ/yr of heat demand at 201 sites. This represents 43% of all surplus heat. Over half the energy recovered is from just 15 sites, with 10 sites representing over half the demand. The potential for a heat network around these large users and suppliers may be economically attractive. Fig. 6-23 shows geographically where sites involved in heat transportation are located. The area of the data points indicates the amount of heat recovered or demanded. A large potential exists around the iron and steel plant in Teesside. A large number of sites around Chester show potential for a heat network in addition to relatively smaller clusters near Falkirk, South Wales and the Thames estuary.

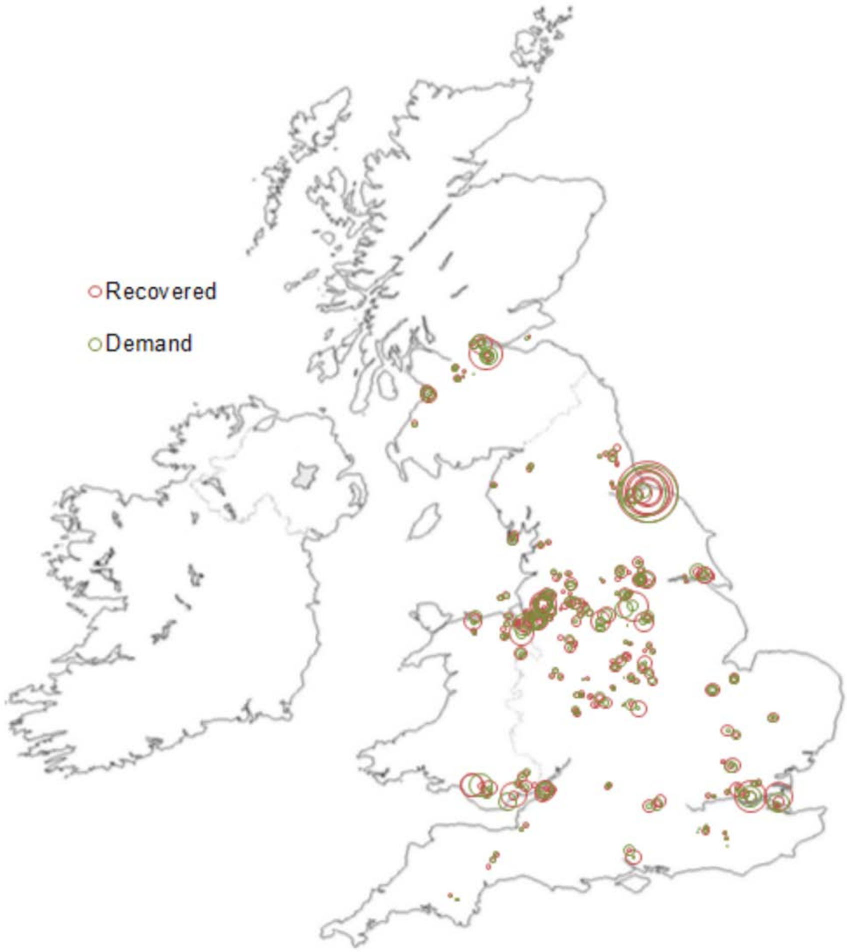

Fig. 6-23: Location of recovered heat and demands assuming a 10km possible transportation distance with 50% efficiency. Area of points represent the energy recovered or demand fulfilled.

Fig. 6-24 shows the proportion of total surplus heat recovered through heat transport technologies and the proportion of sites at which this is possible. The results shown are for the case of the mean heat recovery potential with a 10km possible transportation distance. The results show the heat recovered and the subsector this takes place at, rather than the heat delivered.

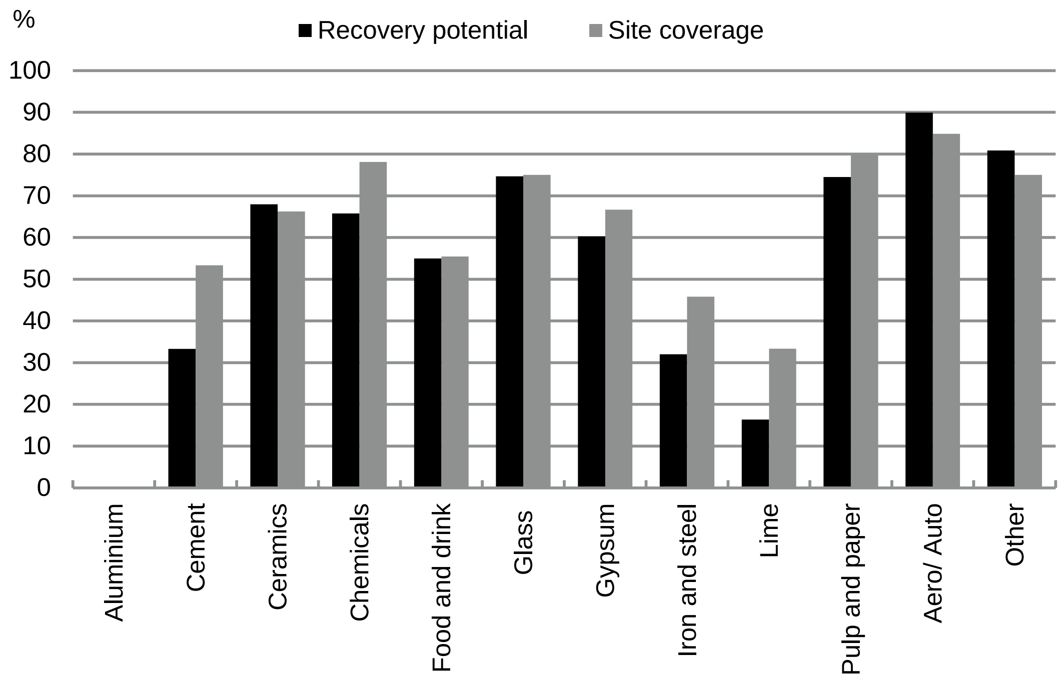

Fig. 6-24: Proportion of total recovery potential realised with offsite recovery and proportion of sites at which this is possible. Subsectoral split by where energy is recovered from.

6.3.7 Combined results

Fig. 6-25 shows the annual heat recovered for each of the end uses examined here, where the heat available is dependent on what is left after the more 'attractive' technologies, according the hierarchy introduced in section 6.2.7, have been applied. The Iron and steel subsector is not shown, it would recover 3.3PJ/yr for use on-site and 23.5PJ/yr through heat-to-power technology. The results shown are for the case of the mean estimation of surplus heat, they also use an upper temperature limit of 300°C for absorption chilling. The totals shown in Fig. 6-25 are the heat recovered, not the useful output. Two results are shown for heat transportation, firstly for a 10km possible transportation distance. What could additionally be recovered with a 40km transportation distance is also shown.

All surplus heat is available for on-site heat recovery as before so these results are unchanged at 19.1PJ/yr. As heat pumps use temperatures less than 100°C the use of this technology is unaffected by on-site heat recovery. Fig. 6-25 illustrates how small this potential is in comparison to other technologies. Surplus heat to absorption chilling drops to just 0.06PJ/yr in the Food and drink subsector and 0.14PJ/yr in Chemicals (from 2.1 and 2.2PJ/yr respectively). Heat-to-power technology now recovers 33PJ/yr. This is compared to 46PJ/yr when all surplus heat is available for use in heat-to-power technology. Most of this loss of potential comes from the Chemicals subsector reusing surplus heat in other ways. After these options for reusing surplus heat have been applied there is little potential left for transport to other sites. With a 10km transportation distance 1.0PJ/yr can be recovered for transportation between sites, if the transportation distance increases to 40km this increases by 1.1PJ/yr. After the combination of heat recovery technologies have been applied only 0.3PJ/yr of total surplus heat remains.

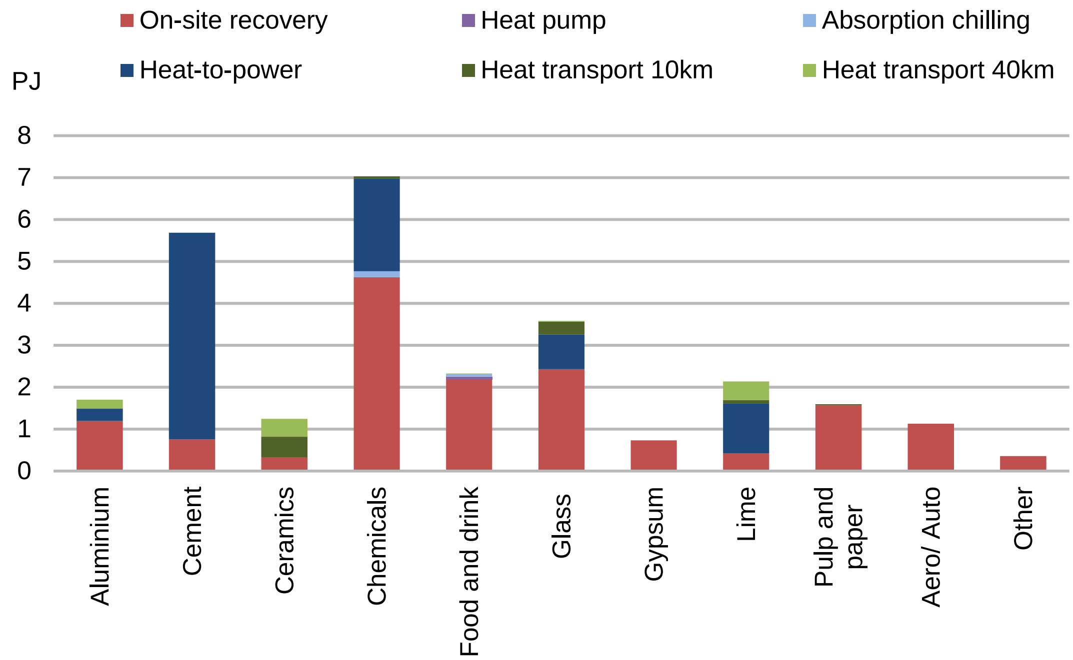

Fig. 6-25: Annual heat recovered through a combination of measures, according to the proposed hierarchy.

Fig. 6-26 shows the carbon dioxide emissions saved through reusing waste heat. Results are shown both for the case of all heat being available for a particular technology and the combined case. The transport and combined results are for the case of the mean heat recovery. Heat transport results show the case for a 10km possible transportation distance and 50% efficiency and the increased potential with a 40km possible transportation distance with a 75% efficiency. The carbon dioxide emissions saved assumes heat would otherwise be supplied by a natural gas powered boiler with 80% efficiency, and electricity would otherwise by supplied by the grid. For absorption chillers it is assumed that alternative electrically powered refrigeration equipment would be used with a COP of 4. Emissions factors are taken from DEFRA/DECC guidelines for company reporting (AEA 2011a). Only energy-related emissions are accounted for, the embodied emissions in installed equipment are not included. For comparison with the savings here, in 2010 onshore wind power in the UK totalled 4036.7MW of capacity and generated 26PJ (DECC 2012b). Assuming the mean emissions factor for the grid this saved approximately 3500ktCO_{2e}.

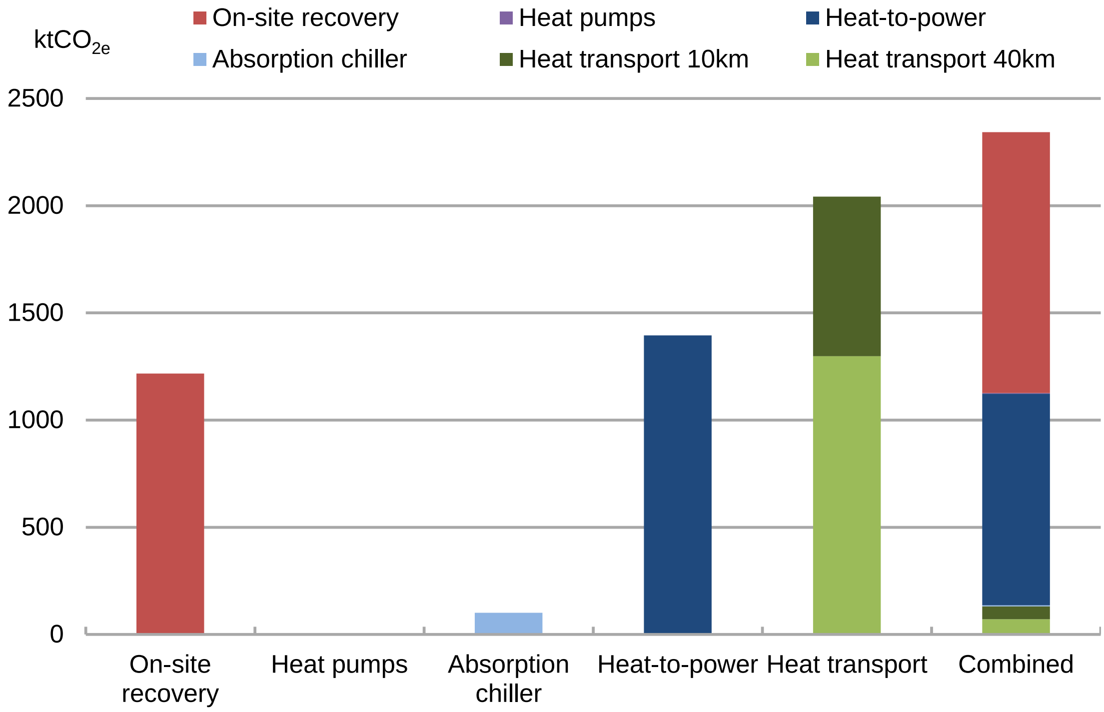

Fig. 6-26: Annual carbon dioxide emission savings through heat recovery technologies.

6.4 DISCUSSION

6.4.1 Comparison with other studies

A report by the US Department of Energy (2008) estimated that 20 to 50% of industrial energy input is lost as waste heat. Whilst this does not represent what it would be technically possible to recover it shows both the scope for surplus heat recovery and the high uncertainty regarding the potential. Here the technically recoverable waste heat potential as a proportion of heat demand was estimated as 7-14%. In regards to studies specific to the UK, The Office of Climate Change estimated annual surplus heat recovery potential in UK industry at 18TWh (65PJ) in 2008, this figure was based on conservative estimates and considerable uncertainty (BERR 2008b). This figure is comparable to the 37-73PJ total recovery potential identified here. Although there are various heat maps of the UK that include non-domestic users of heat (DECC 2012i, Loughborough University 2012, The Scottish Government 2012) it is not known of any that include information on heat recovery potentials. At a subsector level previous estimates of waste heat recovery potential are 48PJ/yr in Chemicals (including plastics and rubber), 8.3PJ/yr in Food and drink and 4.5PJ/yr in Paper and Board (Carbon Trust 1996). A comparison to Fig. 6-7 shows the potentials identified here are considerably less, especially so for the Chemicals subsector. Some of this difference may be down to the partial coverage of subsectors provided by the EU ETS, but it also illustrates the conservative nature of the estimations used here.

6.4.2 On-site recovery

The potential for heat recovery on-site is estimated as 15-23PJ/yr. For perspective this is equal to the space and hot water heating demand for approximately 272,000-418,000 homes[19] or 3-5% of the heat demand for the sites analysed here. What cannot be accounted for in the current analysis is on-site recovery within the same temperature band of the analysis that may, in practice, be possible (for example from a source of 400°C to a sink of 200°C). More defined temperature demands could allow a more accurate analysis, in this regard, and may reveal further opportunities to recover heat on-site. In practice there may also be opportunities to preheat combustion air, product or other medium where the heat sink can be at a different temperature than that specified by the heat demand. However these opportunities are unknown without more detailed studies of specific subsectors and sites, which are recommended as an extension of this work, see section 6.4.8. Taking into account these considerations, it is thought that this analysis will likely underestimate the technical potential for recovery on-site and there may be opportunities to recover heat at higher temperatures than those specified here (which would limit the cost of the heat recovery). The majority of the identified on-site potential involves recovery at low temperatures (below 100°C) from higher temperature bands, which causes additional costs in comparison to recovering at higher temperatures (100-500°C), mainly due to issues of heat exchanger

[19] Based on 18,600kWh mean energy use per household and 82% of domestic energy being used in space and water heating (Palmer and Cooper 2011).

corrosion (see section 6.1.1). These costs could potentially be lowered by further research and development into low temperature heat exchangers. A study by the US Department of Energy (2008) into waste heat opportunities in US industry found research and development of low temperature heat exchangers to be key to furthering the use of waste heat in industry. Additionally as the technical heat recovery potential estimated here does not include the latent heat of the source, if heat recovery below the dew point was allowable the amount of heat recoverable would increase. Due to the uncertainties involved in this analysis, its conservative approach and for simplification, the additional heat recoverable from capturing the latent heat was not included here.

6.4.3 Heat pumps

The potential for heat pump use in industry in the current analysis is limited to a single subsector, Malting. It is confirmed by another study that the Malting subsector has considerable potential for heat pumps (Carbon Trust 2011a). The potential for heat pumps within Maltings could fulfil a significant proportion of the subsector's heat demand (6-12%). Assuming the heat supplied by heat pumps would otherwise have been supplied with a natural gas boiler, and that the electricity used by the heat pumps is supplied by the national grid the overall annual carbon savings using heat pumps at the malting sites is estimated to be 1.8-3.5 ktCO_{2e}. With a lower carbon electricity supply these savings would be higher. In reality the potential for heat pumps throughout industry is thought to be considerably higher than the single subsector identified here. Here a single source of recovery potential is identified for each site. In practice there will be low temperature surplus heat from a variety of sources, including compressors and chillers, which can supply surplus heat at 30-60°C (Hita et al. 2011). This could be well used as a source for heat pumps if a sufficient demand exists. Air and ground source heat pumps can also be used within industry to supply low temperature heat where a suitable surplus heat source is not available. Chapter 7 includes an estimation of heat pump opportunities throughout the Food and drink subsectors. The economic use of heat pumps is highly dependent on the relative price of the conventional heat source (often natural gas, used to fuel boilers) to electricity. Expected technical improvements in heat pump technology will mean the temperatures that can be supplied and the temperature drop between the source and sink will increase, which will lead to more opportunities for their use in industry.

6.4.4 Absorption chilling

The electricity use for chilling in 2005 was 12PJ for Food and drink and 11PJ for Chemicals (BERR 2008a). This gives a cooling demand of 48PJ/yr for Food and drink and 44PJ/yr for Chemicals, assuming a COP of 4 for refrigeration equipment. Quantitatively there is therefore sufficient cooling demand to be filled by that potentially generated through absorption chilling of 0.8-2.0PJ/yr and 0.9-2.1PJ/yr for Food and drink and Chemicals respectively (using the more realistic scenario of absorption chillers with a 300°C upper temperature limit). Absorption chillers would not be suitable for supplying low temperature cooling requirements however. In most applications absorption units chill water to approximately 5°C (Horbaniuc 2004), this will limit their use. Whether the use of this technology would be suitable at a site level would require a more detailed examination of cooling demands. Absorption chillers can also be used to supply a hot water demand (Garimella 2012), which is not examined here. In the Food and drink sector where there is a large demand for hot water for cleaning this could make the use of absorption chillers more attractive. When on-site heat recovery is prioritised the identified potential for absorption chillers drops considerably. There may also be opportunities for the use of absorption chillers outside the Chemicals and Food and drink sectors. The increased use of air conditioning for human comfort and for cooling large computer systems forms a significant potential, with absorption chilling being well suited to these purposes. Other subsectors may therefore find a use for this technology.

6.4.5 Heat-to-power

Heat-to-power can be an attractive prospect for using surplus heat. Electricity can be used in a wide range of processes and also relatively easily exported if there is not a sufficient demand on-site (some additional connections and expense may be required in this case for connecting to the national grid). Where heat-to-power technology is used to supply on-site electrical demands it can result in smaller capacity requirements for electrical equipment used in interconnection and distribution of grid electricity (Cunningham and Chambers 2002). In new builds the savings on this equipment can completely offset the capital costs of the heat recovery system (Cunningham and Chambers 2002). The use of heat-to-power technologies also insulates a company from the volatility in electricity prices. The total demand for grid electricity of the sites included in this analysis is 105PJ/yr. Electricity generated by heat-to-power technology could supply 6-13% of this demand, or, for comparison, the electricity demand of 422,000-883,000 households[20]. This amount of displaced electricity would save 905-1890ktCO_{2e} annually. This is a higher carbon saving than that from reusing heat on-site, however if the electricity sector is decarbonised this would fall.

The subsectors with the highest potential for heat-to-power technology in the current work, Cement and Iron and Steel, show good prospects for this technology in practice. In the Cement subsector where surplus heat availability was based on a modern efficient plant (McKenna 2009) the limits of recovering heat for preheating and use earlier in the process are being reached (IEA 2009). The remaining surplus heat has found a use in conversion to power in some plants (AEA 2010b), this is further explored in Chapter 7. A heat-to-power scheme is also planned for the Port Talbot steelworks, based around the basic oxygen furnace (Tata Steel 2011). It is predicted that this project will produce 10MW of electricity (Tata Steel 2011). The predicted output from a heat-to-power scheme on the Port Talbot BOF using the current analysis was 4.3-8.6MW.

Giving preference to reusing heat on-site and absorption chilling reduces the power generated by surplus heat to 4.2-9.4PJ/yr (from 6.7-14.0PJ/yr). That the Cement and Iron and steel subsectors do not have a large potential for reuse on-site means the heat-to-power potential is not reduced excessively. After the use of heat-to-power technologies

[20] Assuming 23.7% of domestic energy demand is electrical (Palmer and Cooper 2011), giving approximately 4400kwh/yr of electricity demand per household.

there may be further opportunity to use the waste heat output from the heat-to-power equipment at low temperatures (Pehnt et al. 2011), this is not considered here but may lead to increased opportunities to save energy and carbon through the use of other technologies using this heat source (for example heat pumps). This is an example of heat cascading, utilising heat multiple times at different temperatures, as introduced in Chapter 2. Whether due to the conservative nature in identifying waste heat potentials, or in setting the minimum temperature and power requirements for use in waste heat-to-power technologies, it is thought that existing opportunities to those identified here exist. For instance other studies have highlighted potential for waste heat-to-power technologies in the Food and drink sector (Handayani et al. 2011, Law et al. 2011), but here there is very little potential identified (see Fig. 6-17).

6.4.6 Heat transportation

The potential for heat transportation calculated here is more speculative than it is for other technologies; the possible distance of transportation and efficiency of the transfer, being open to considerable uncertainty. Additionally the potential for heat transport after more economically attractive options for reusing the heat have been explored is relatively small (see Fig. 6-25 and Fig. 6-26). The main barriers to the potential for reusing waste heat between sites are the cost of heat pipelines (or other transportation options) and the security of supply, if one site relies on another for its heat supply (or conversely for income by selling surplus heat) then disruptions in production or closure of one site can considerably affect the other.

The existence of a heat network, involving multiple users and the regulation of such a market to protect the stakeholders (similar to that which exists for electricity and gas) would facilitate the sharing of waste heat between sites, and may make this option more attractive than other possibilities for reusing waste heat from industry. Such a heat network could exist between multiple industrial users, geographical areas that show good potential in this regard are shown in Fig. 6-23. Another option that may be more attractive economically and can involve industrial sites not located near other industrial sites is the use of waste heat within a district heat network that could include industrial, commercial and domestic buildings. A district heat network spreads the costs of such a network between a number of users, lowering costs. Industrial sites could act as either a user of heat, or supplier of heat in such a network.

In the UK, district heating is currently little used. Approximately half a million homes in the UK are currently supplied by district heating systems (BERR 2008b). This represents less than 2% of the country's heat demand (Poyry Energy Consulting 2009). Other countries have considerably greater use of this technology with Denmark supplying 70% of heat demands through heat networks, Finland 49% and Sweden 50% (DECC 2012h). Heat networks are an option that is favoured for reducing energy use and GHG emissions associated with heat in the UK (DECC 2012h). Analysis suggests than approximately 50% of heat demand in England is concentrated with sufficient density (3000kWh/km^2) to make heat networks worth investigating (DECC 2012h). It is likely heat networks would start small and expand and become more interlinked over time. Initial priorities set out by DECC (2012h) include making use of existing waste heat resources from industry, the current work therefore has some significance. Examples of manufacturing plants integrating with district heating systems include two refineries supplying 30% of the annual heat demand of a district heating system in Gothenburg (Werner 2004), Rotterdam also has a heat network for which the main heat source is industrial waste heat (DECC 2012h). Recently the possibility of a district heat system supplied by the Port Talbot integrated steelworks has been investigated (This is South Wales 2010). Industrial sites as users in a network have the advantage of having a year round heat demand. Connective Energy, a commercial enterprise set up by the Carbon Trust in partnership with Mitsui Babcock and Triodos Bank used a bottom-up study in 2007 to estimate the market potential for surplus heat, by creating a heat network and facilitating transactions, as 40TWh/yr (144PJ/yr) (BERR 2008b). Most potential users identified were low temperature industrial processes, showing the suitability of industrial sites for the early stages of expanding heat networks. District heat networks generally transport heat at 80-120°C (DECC 2012h), where higher temperatures are required for industrial applications laying steam pipes at the same time as the lower temperature district heating networks would reduce costs. This approach was taken in the Copenhagen network which includes hot water and steam pipelines (DECC 2012h).

An extension to the current work could involve combining the work undertaken here with information on non-industry heat loads to highlight locations where the required heat density for a district heat network and sources of industrial waste heat interact. Such information on non-industrial heat loads has been identified in work undertaken by Loughborough University (2012), DECC (2012i) and The Scottish Government (2012).

6.4.7 Drivers and barriers to heat recovery technologies

Barriers to the increased use of waste heat are common to many energy efficiency projects in manufacturing and include lack of capital and competition with production orientated projects; lack of information, staff time and expertise to explore opportunities; and risk aversion to unknown technologies (see Chapter 4 for a discussion of barriers to energy efficiency projects). An important consideration for companies when installing a waste heat recovery measure is that is does not adversely affect the product or other manufacturing processes. A review of barriers to energy efficiency projects, specifically focussing on low temperature heat utilisation was conducted by Walsh and Thornley (2012). The findings specific to low temperature heat utilisation found lack of infrastructure to be a key barrier. It has already been discussed above how the existence of a heat network may allow waste heat to be more easily utilised. A driver to installing heat recovery equipment, in addition to those previously discussed in this work relating to improving energy efficiency (see Chapter 4), is that other equipment can be downsized and this can save costs (this could be seen as an example of indirect benefits). This is discussed above in reference to waste heat-to-power equipment, but also applies to traditional heat recovery, by lowering the heat load on utilities smaller boilers and other equipment can be used, which can reduce capital costs. Conversely if heat recovery equipment is installed and smaller heat utilities are not purchased (which could be expected if the existing utilities are still operational) then the reduced heat load can lead to inefficient operation, limiting the positive effects of the heat recovery equipment. Another driver to waste heat recovery is that reducing the temperature of heat rejected to the environment decreases thermal pollution. Whilst at a global level the GHG emissions associated with heat production are more significant (Zevenhoven and Beyene 2011) at a local level reducing thermal pollution can be an important consideration, especially in the case where cooling water is exhausted into local water courses.

6.4.8 Further work suggestions and related issues

This section covers more general comments and suggestions for further work that have not been covered within any of the technology specific discussion above.

The analysis presented here is intended to be indicative of the situation regarding heat recovery and used to highlight broad opportunities rather than precise potentials. There is generally a conservatism applied to the recovery potentials and the other salient parameters in the analysis. In part this conservatism was applied due to a lack of detailed data in some areas. A peak can be seen in the recovery potential shown in Fig. 6-5 in the 100-200°C temperature band. This is as large proportion of heat is used in steam systems [this was assumed for a number of subsectors for which there was not sufficient data to give a more detailed picture of energy use (McKenna 2009)] and a recovery potential at 150°C was assumed from steam systems. As a comparison a study of recovery potentials in US manufacturing (US DOE 2008) concurred that for a boiler using conventional fuels and already employing heat recovery technology the figure of 150°C is appropriate. However for alternative fuels this would rise to 177°C and for boilers without heat recovery a figure of 260°C was used (US DOE 2008). This goes to illustrate the conservative approach taken to the values of heat recovery potential used here, it is assumed that attractive opportunities for heat recovery had already been taken and is why the majority of potential lies in low temperature heat recovery or more costly technologies. In reality some 'low hanging fruit' in terms of heat recovery opportunities may remain, especially in less energy-intensive subsectors (see Chapter 5), including those not well represented in the EU ETS.

To build on this indicative assessment of potential for heat recovery technologies more detailed work, including case studies, would help refine this potential and identify drivers and barriers to the installation of equipment at specific sites or industries. The expected costs could also be identified in these studies, an area that was not explored here due to the large uncertainties surrounding cost data, especially when applied to a diverse group of sites. The domination of large sites in the overall potential for waste heat recovery indicates that a relatively small number of detailed studies may be able to assess a significant proportion of the total potential. Such detailed studies would also be able to identify methods to integrate different heat recovery technologies and optimise the site energy usage. An example of such a technique is pinch analysis used to design a heat exchanger network (HEN) when a number of hot and cold streams exist (Furman and Sahinidis 2002). Such a technique applied to a steel manufacturer identified significant savings (Matsuda et al. 2012). Detailed studies would also be able to identify resources beyond those examined here, such as low temperature heat sources that may be suitable for use with heat pumps. Some of these additional heat sources may arise after primary heat recovery has occurred, so that heat can be reused multiple times at different temperature levels [this idea is often known as a 'heat cascade' (Van Gool 1987)]. Additionally options that are not identified here for heat recovery, such as air and product preheating, space heating, and drying (including biomass drying) could be examined.

Case studies of heat recovery potentials would also help place heat recovery opportunities within the wider aim of energy efficiency and emissions savings. Reusing surplus heat is essentially exploiting an inefficiency, and where in some cases surplus heat is inevitable (see section 6.1 for a discussion on this) an inefficient process may lead to increased waste heat availability. In this case it is normally preferable from an energy and economic viewpoint to improve the efficiency of the process, rather than use the increased waste heat. Improvements can be simple and low (or zero) cost, examples would be improved insulation and maintenance. Measures that involve more resources may be improving the control of the process and better design relating to heat requirements. An alternative to the process may also be available, involving substantial redesign. In some cases a heating process can be replaced by a non-thermal alternative and save considerable energy. For example mechanical dewatering is an alternative to thermal drying (Reay 2008) and membrane technology is a potential replacement for thermal separation (AEA 2010b). In the pulp and paper industry a move away from thermal processes could reduce SEC by up to 90% (De Beer et al. 1998). Waste heat recovery holds potential for improving the energy efficiency of manufacturing but should also be considered alongside other options for providing heat in a lower carbon manner.

There are a few general areas regarding the data used is the study, that could be improved. These are:

1. Increasing the proportion of industry in the analysis.
2. Updating data for a more recent time period.
3. Better defining some subsectors of industry.

The coverage of the analysis presented here is limited to the sites involved in the National Allocation Plan (NAP) of the EU Emissions Trading System (EU ETS). This covers approximately 60% of final energy demand in industry and 90% of energy-intensive industry (see Chapter 3). Although the largest energy using sites are covered there may also be significant savings potential at other sites. The sites involved in the EU ETS have an additional driver to improving efficiency and so may be more likely to implement heat recovery measures (see Chapter 4), however by this rationale they are also more likely to have already implemented saving measures (see Chapter 5 for further discussion on this) so the sites not covered may hold significant potential savings, although the waste heat available is likely at lower temperatures.

As the data used here refers to the years 2000-2003 it could be updated to a more recent time period, if a suitable source exists, this is discussed further, along with the expected changes in energy use since the time period of the data in Chapter 3 and Chapter 5. As a final consideration there are subsectors within this analysis that are treated in a generic fashion, with heat demand assigned to steam systems. These are mainly within the Food and drink and Chemicals subsectors where heterogeneity of energy use makes analysis more difficult. This is an area that could be improved. Additional options for the reuse of surplus heat that may become more viable in the future include water desalination and hydrogen production (Ammar et al. 2012), these could be included in a future update if appropriate.

6.5 SUMMARY

A database of the heat demand, heat recovery potential and location of United Kingdom industrial sites involved in the European Union Emissions Trading System, was used to estimate the potential application of different heat recovery technologies. The options considered for recovering the heat were recovery for use on-site (using heat exchangers), upgrading the heat to a higher temperature (using heat pumps), conversion of the heat energy to fulfil a chilling demand (using absorption chillers), conversion of the heat energy to electrical energy (using Rankine cycles), and transport of the heat to fulfil an off-site heat demand. The assessment was undertaken for each of these options based on the existence of a suitable demand, and the heat source being of suitable temperature, and of a great enough size, to exceed the minimum equipment size.

A broad analysis of this type, which investigates a large number of sites, cannot accurately identify site level opportunities. However the analysis can provide an indicative assessment of the overall potential for different technologies. The greatest potential for reusing the identified surplus heat was found to be recovery at low temperatures, utilising heat exchangers; and in conversion to electrical power, mostly using organic Rankine cycle technology. Both these technologies exist in commercial applications, but are not well established. Support for their development and installation could increase their use. The overall heat recoverable using a combination of the technologies examined was estimated at 52PJ/yr, saving over 2.0MtCO_{2e}/yr in comparison to supplying the energy outputs in a conventional manner. A network and market for trading in heat, and the wider use of district heating systems, could open considerable potential for exporting heat from industrial sites to other users, both within and outside the industrial sector.

There is potential to extend this work, within the current framework data could be updated in terms of the time period, widened to those sites outside the EU ETS, and certain subsectors could be better modelled. Including non-industrial heat demands when assessing opportunities for exporting surplus industrial heat to other users could highlight areas where waste heat could be used as a heat source, within a district heating system. Case studies that examine site level opportunities for waste heat recovery, especially in those areas found to have high potential here would be valuable in gaining more accurate information on opportunities, albeit on a smaller scale, in comparison to this broad, indicative study.

CHAPTER 7

SUBSECTOR LEVEL OPPORTUNITIES: FOOD AND DRINK AND CEMENT

The variation in energy use throughout the manufacturing sector is the greatest challenge in analysing its improvement potential. To illustrate this variation, and as an example of how to approach the analysis of two different subsectors, the Food and drink and Cement subsectors are examined in the current chapter. In 2010 the industrial sector was responsible for 108MtCO_{2e} of GHG emissions, and a final energy demand of 1.03EJ (this is based on the conventions and datasets discussed in Chapter 2). The Food and drink and Cement subsectors, as defined below, are responsible for approximately 10% and 6% of industrial emissions respectively (on a final energy basis these values become 13% and 3%). The Food and drink sector is responsible for approximately 17% of manufacturing GVA and Cement manufacture just 0.2% (ONS 2012a). The energy intensity of the Cement sector is therefore much greater than that for the Food and drink sector, there are other considerable differences. The Food and drink subsector outputs a large number of products through many process routes, a demand for low temperature heat, primarily fuelled by natural gas is the dominant process. The majority of sites are small users of energy, with energy representing a small proportion of operational costs. In contrast the Cement subsector’s energy demand and emissions are dominated by a single homogeneous product, and by the kiln process. The kiln is primarily fuelled by coal and waste fuels, and is responsible for significant amounts of process emissions. There are a small number of large energy users, and energy use forms a substantial proportion of operational costs. A study of these two subsectors therefore offers a contrast of energy use and improvement potential between a homogeneous energy-intensive subsector and a heterogeneous non-energy-intensive subsector. This chapter aims to examine the Food and drink and Cement subsector in terms of:

- The products and processes responsible for GHG emissions.
- The characteristics of the subsectors regarding energy use, including the drivers and barriers to improving energy efficiency.
- The historical changes in energy use and reasons for these changes (including a decomposition analysis).
- Future potential for improving energy use.

The chapter therefore draws on techniques that have been applied to the whole manufacturing sector earlier in the thesis. This work allows a comparison of these subsectors, indicating the variability throughout the manufacturing sector.

7.1 THE FOOD AND DRINK SUBSECTOR

The Food and drink subsector manufactures a wide range of products, making use of many different processes. The analysis of the subsector therefore presented a challenge akin to that of examining the whole manufacturing subsector. In this section the energy use between different subsectors of Food and drink is examined, this approach is contrasted to examining the energy use between different processes. A decomposition analysis is undertaken to determine the recent changes in energy demand, and reasons for these changes, to help better understand the character of the subsector. The energy efficiency opportunities through applying a number of technologies that focus on providing low temperature heat in an efficient manner are then examined, and the prospects for their adoption within the Food and drink sector discussed. During the course of the work case studies were begun with three Food and drink manufacturers in the South West region of the UK. These were a dairy products manufacturer, a food packaging company, and a poultry product manufacturer. These case studies did not supply useful information for the energy analysis, but did give insight into the character of such companies. These findings are referenced in the current section where applicable.

7.1.1 Current energy use

7.1.1.1 Subsectoral split

The Food and drink subsector is represented by 33 four digit SIC codes, indicating the heterogeneity of the subsector. Fig. 7-1 shows the energy demand of the subsector when split into thirteen subsectors, with information taken from the ECUK dataset (DECC 2009c). This grouping is a combination of three and four digit SIC codes and is based on knowledge of the processes and products produced within the groupings; data limitations; and how the food and drink subsector is split by other resources, such as the CCAs. The subsectors shown in Fig. 7-1 should therefore represent the main energy users, it was hoped each subsector would have a relatively well defined production process (this is discussed further below). The top five energy using subsectors comprise approximately 60% of the total energy demand on a primary and final energy basis. There is some concern about the accuracy of energy demand data at this high level of disaggregation. Additionally data on energy use at this level of disaggregation is not available for recent years (see Chapter 2 for more discussion on datasets and disaggregation level). The totals shown in Fig. 7-1 represent the mean from 2002-2006, with the highest and lowest energy demand over this period removed, in order to remove the effect of any large year-to-year fluctuations caused by data inaccuracies.

Fig. 7-2 illustrates the variation between subsectors of the Food and drink subsector. The parameters used to define energy-intensive industry in Chapter 4 are represented. Fig. 7-2 shows energy intensity (here represented by primary energy demand per £ of value produced), the percentage of production costs represented by water, and energy and the energy use per site. The dotted lines indicate the values for energy-intensive (EI) classification, as defined for the manufacturing sector in Chapter 4. Similarly to Fig. 7-1 data is the mean of 2002-2006 disregarding the highest and lowest results over this period. Disaggregation was not available at the same level as in Fig. 7-1.

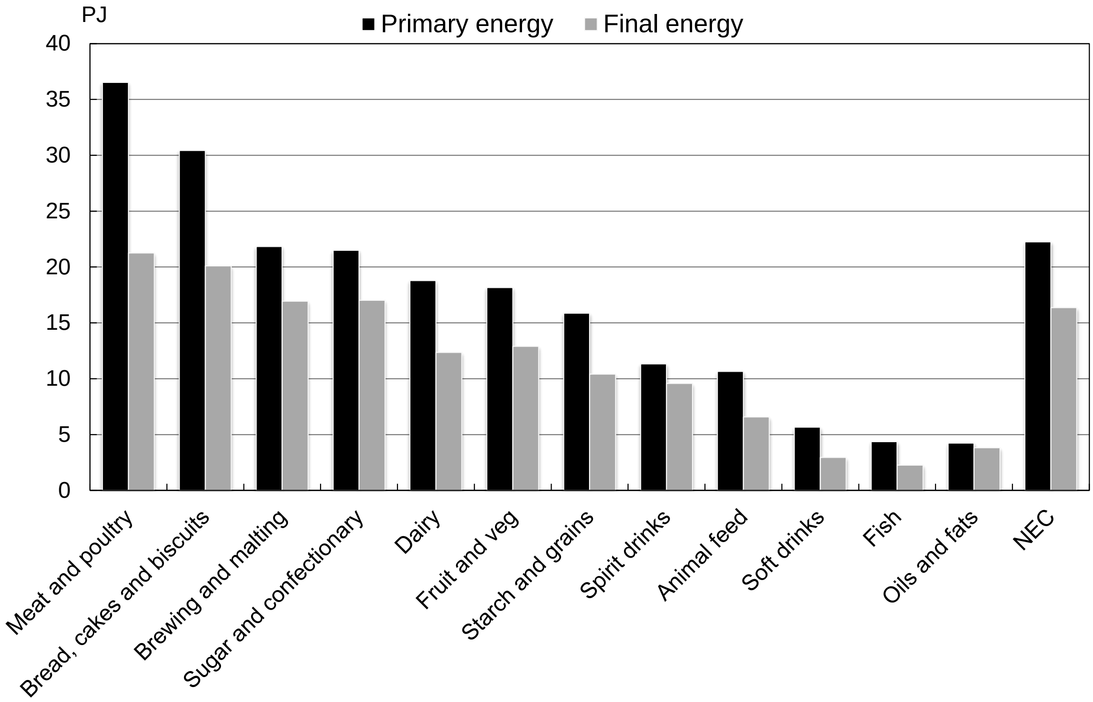

Fig. 7-1: Primary and final energy demand for subsectors of Food and drink. Totals shown are for 2002-2006 disregarding the highest and lowest energy demands over this period (DECC 2009c).

The variability within the Food and drink sector as represented in Fig. 7-2 is not as great as within the manufacturing sector as a whole, although it is still considerable. Based on the analysis of Chapter 4 subsectors of Food and drink that are classified as energy-intensive are:

- Oils and fats
- Starch and grains
- Distilled drinks and malting

Food and drink as a whole is classified as non-energy-intensive. By comparing the results of Fig. 7-2 to Fig. 7-1 it can be seen that the energy-intensive subsectors of Food and drink generally comprise a small amount of energy demand in the subsector. Approximately 81% of primary energy demand in Food and drink is within subsectors classified as non-energy-intensive. This indicates there are generally weaker drivers to energy efficiency improvement in the Food and drink sector, especially within those subsectors that are the largest users of energy. The Food and drink subsector comprises a significant proportion of the non-energy-intensive subsector. It represents approximately 25% of final energy demand within the non-energy-intensive subsector (as defined in section 4.3 at the higher level of disaggregation).

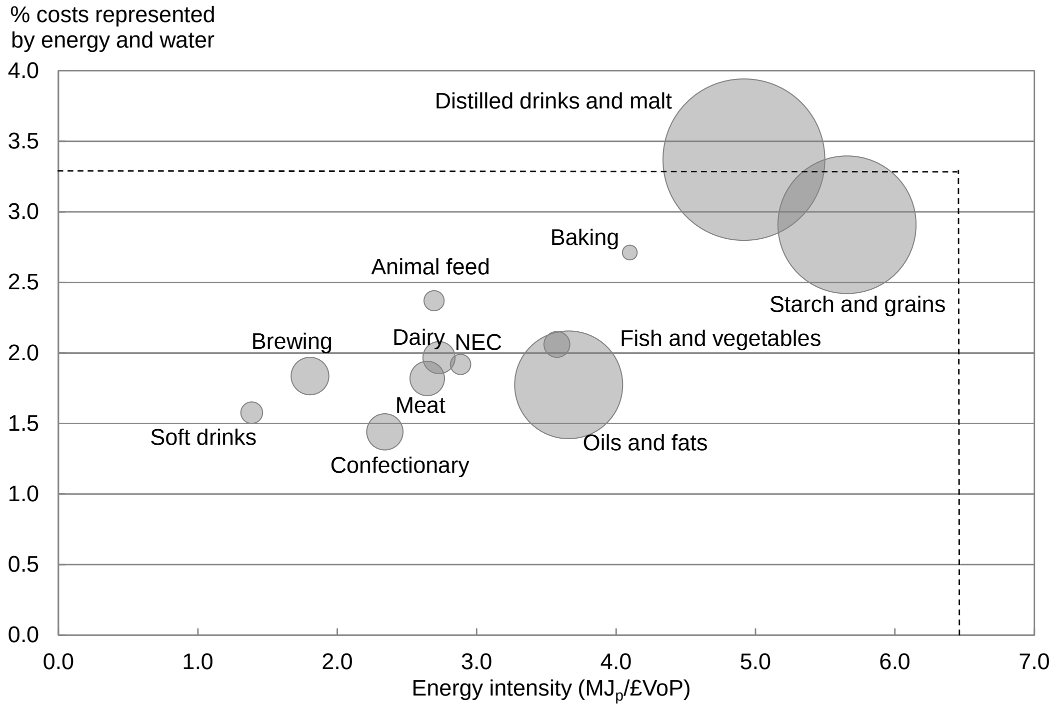

Fig. 7-2: Primary energy intensity, percentage of costs represented by energy and water and energy use per site (represented by the area of the data points) for the Food and drink subsector, 2002-2006. Dotted lines indicate limits of EI criteria.

7.1.1.2 End use split

The European Commission (2006b) identified 57 different uses of energy within Food and drink manufacturing, these can broadly be grouped under the headings: Material reception and preparation; Size reduction, mixing and forming; Separation techniques; Product processing technology; Heat processing, Concentration by heat; Processing by removal of heat, Post processing operation and Utility processes. A study of energy use throughout the EU manufacturing sector (AEA 2000), found the following operations to make up the vast amount of energy use in Food and drink:

- Baking, Kilning or Roasting – heating in a dry or moisture controlled atmosphere
- Blanching – immersion in steam or boiling water to aid preservation or peeling
- Chilling & Freezing – mostly mechanical vapour compression with some cryogenic plant
- Cooling (without direct refrigeration) – using forced or convective air or water.
- Cooking
- Distilling – evaporating vapour from a mixture & condensing for purification or extraction, mainly steam driven
- Drying – usually by application of heat but alternatives include freeze, microwave and vacuum.
- Evaporation – use of heat to drive water from a solution.

- Extrusion – mechanical pressurisation of product through defined nozzles
- Fermentation – simmering for long periods with yeast
- Frying
- Heating
- Milling, Grinding or Pulverising
- Mixing
- Pasteurising – controlled heating to achieve a minimum temperature for a specified time
- Separation – preconcentration of fluids using mechanical filtration. Includes sieving, filtration, ultra-filtration, use of membranes and osmotic pressure.
- Sterilisation
- Chilled and Frozen Storage
- Hot washing of machinery and facilities – manual wash down or cleaning in place, often with water at high pressure.
- Building services – heating, lighting, and air-conditioning.

The main energy demanding processes were found to be drying, other separation processes (evaporation and distillation), baking, refrigeration and provision of steam or hot water (AEA 2000). These two studies (AEA 2000, European Commission 2006b) therefore present a diverse mix in energy using processes throughout the Food and drink subsector, however a significant proportion of these processes demand energy in the form of heat.

Fig. 7-3 shows the approximate energy flows from primary fuels to end use within the Food and drink sector in 2010. This is based on various datasets taken from DUKES (DECC 2012b) and ECUK (DECC 2012f) with supplementary analysis. In total this represents 132PJ of net final energy demand, 196PJ of primary energy demand and 10.8MtCO_{2e} of energy-related carbon emissions (there may be some small differences when summing the values shown in Fig. 7-3 due to rounding). Final energy demand is dominated by natural gas (61%) with a significant amount of electricity usage (31%) and small amount of oil (7%) and coal (1%). The domination of low temperature processes within Food and drink can be seen in Fig. 7-3, drying/ separation processes also contribute to the demand for relatively low temperature heat. A large proportion of heat is thought to be supplied by steam systems, although no data on the direct use of steam throughout the UK Food and drink subsector was available. The UK Food and drink Federation (FDF) estimate 49% of the sector emissions are from energy use in boilers, with another 27% from direct heating (FDF 2008). The US Food and drink sector uses an estimated 52% of delivered energy in steam systems (US DOE 2004).

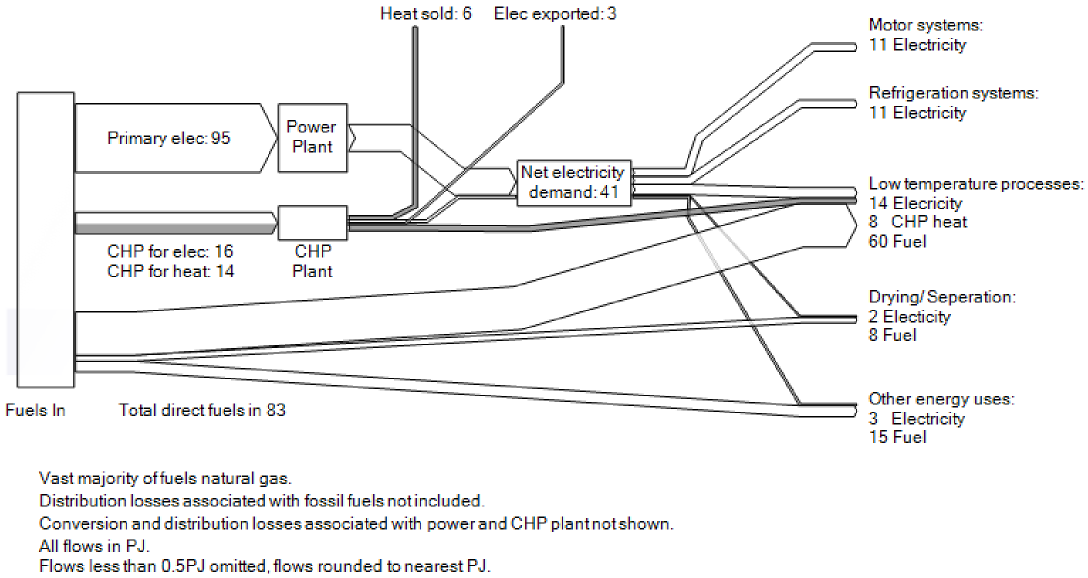

Fig. 7-3: Sankey diagram of UK Food and drink sector, 2010.

7.1.2 Decomposition analysis

Fig. 7-4 shows a decomposition analysis of final energy demand in the Food and drink sector over the period 2001-2007. Results are shown as a percentage of the energy demand in 2001. The LMDI I methodology was used, as detailed in Chapter 5. Similarly to the previous decomposition analysis output was measured by value of production in real terms. The Food and drink subsector was disaggregated into eleven subsectors for this analysis. This was the maximum disaggregation allowed by the data available. The time period of the analysis was limited by data availability to 2001-2007.

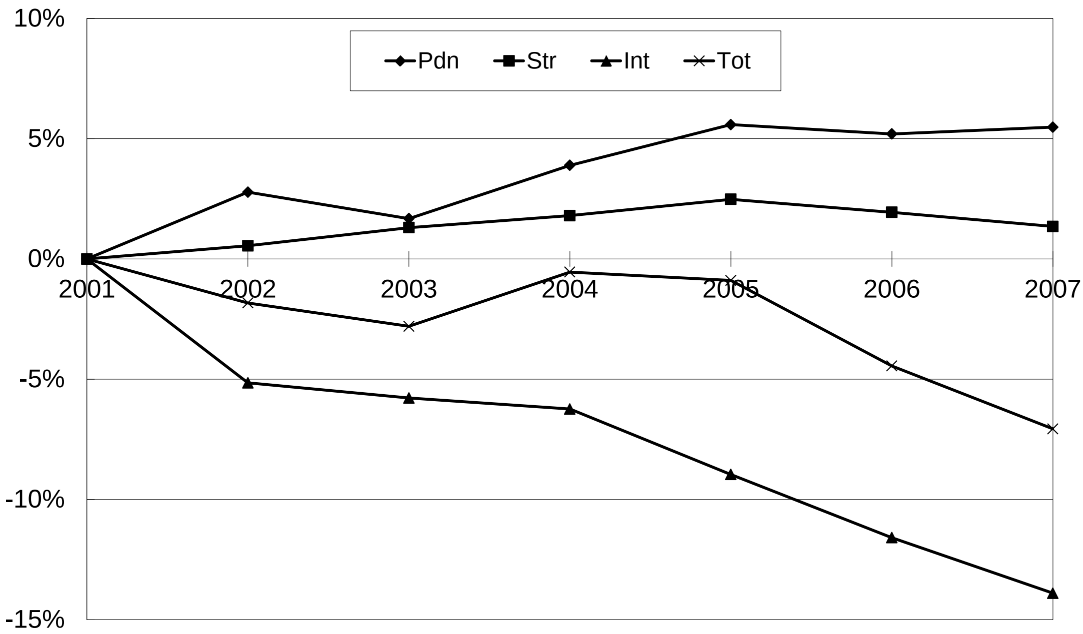

Fig. 7-4: Decomposition of final energy demand in the Food and drink sector 2001-2007.

Fig. 7-4 shows an increase in energy demand due to increased production, and a smaller increase due to shifts in the structure of the Food and drink subsector (both of these effects have been relatively stagnant since 2005). The dominant effect in the reduction of energy demand seen is a falling energy intensity. This presents a generally positive image of the subsector. It is both growing and is steadily reducing its energy intensity. The increase in production seen requires a little further explanation, the Food and drink sector is generally a 'non-growth industry'. Output volume is fairly static but there has been a move to added value products, which is expected to continue (Reason et al. 2009). This is supported by comparing Fig. 7-4 to CCA reports on physical output. In the first target period (2002) of the CCAs output from the Food and drink sector (as included in the CCA) was 37.5Mt, in the fifth target period (2010) it was 37Mt (AEA 2011b). Despite the recession over this period output from the Food and drink subsector has remained fairly constant (see Fig. 3-7 for full details). The production growth effect shown in Fig. 7-4 is therefore thought to be due to an increase in the proportion of higher value added products manufactured. The structural effect would indicate these higher value added products are more energy-intensive. This is consistent with a shift towards a greater amount of processing at the manufacturing site, rather than within the home, as has been seen in the EU (Ramirez 2006).

In explaining the decrease in energy intensity seen it is useful to consider the drivers and barriers to improving efficiency in the subsector, and to put the decomposition analysis within the longer term trend of energy intensity of the Food, drink and tobacco sector, which is shown in Fig. 7-5. The Food and drink subsector is generally risk adverse in nature, there is strong focus on product quality and stringent safety requirements have been seen to increase energy demand in recent years (Ramirez 2006). The subsector's customer base tends to be dominated by a few large retailers meaning margins are small and there is little capital for innovation (Reason et al. 2009). Product life-cycles can be short and so flexibility of equipment is vital, which will often harm efficiency. Large scale adoption of technologies is made difficult by the diverse and fragmented nature of the subsector. Additionally many food manufacturing sites are small, with 92% of businesses in Europe SMEs (European Commission 2006b), efficiency improvement tends to be slower at these small businesses. In the experience of engaging with Food and drink companies it was the current author's experience that they had poor information regarding their current energy use, and very little staff time to focus on energy issues. These companies had shown interest in participating in a case study that examined energy use and efficiency opportunities. Despite these effects improvements are seen in the period studied here (2001-2007) that are comparable to those achieved throughout manufacturing over the same period (for these results refer to Chapter 5). Fig. 7-5 shows that the Food and drink sector has made a fairly constant decrease in energy intensity since the 1970s, indicating small continued improvements in efficiency, part of this trend may also be a switch to less energy-intensive products (structural change was not assessed over this period). The reductions in energy intensity in Food and drink have closely matched those throughout industry since 1990. Previous to this greater relative improvements were seen throughout manufacturing. This was partly caused by a switch to less-energy-intensive manufacturing and also by large reductions in the intensity of some subsectors (particularly those classified as EI subsectors, see Chapter 5 for further discussion). The Food and drink subsector has not shown the same relative improvements in relation to energy intensity as other areas of industry over the period since 1970, but due to this may also have greater potential for further improvement through relatively easily implemented technologies (as discussed in reference to the NEI subsectors in Chapter 5).

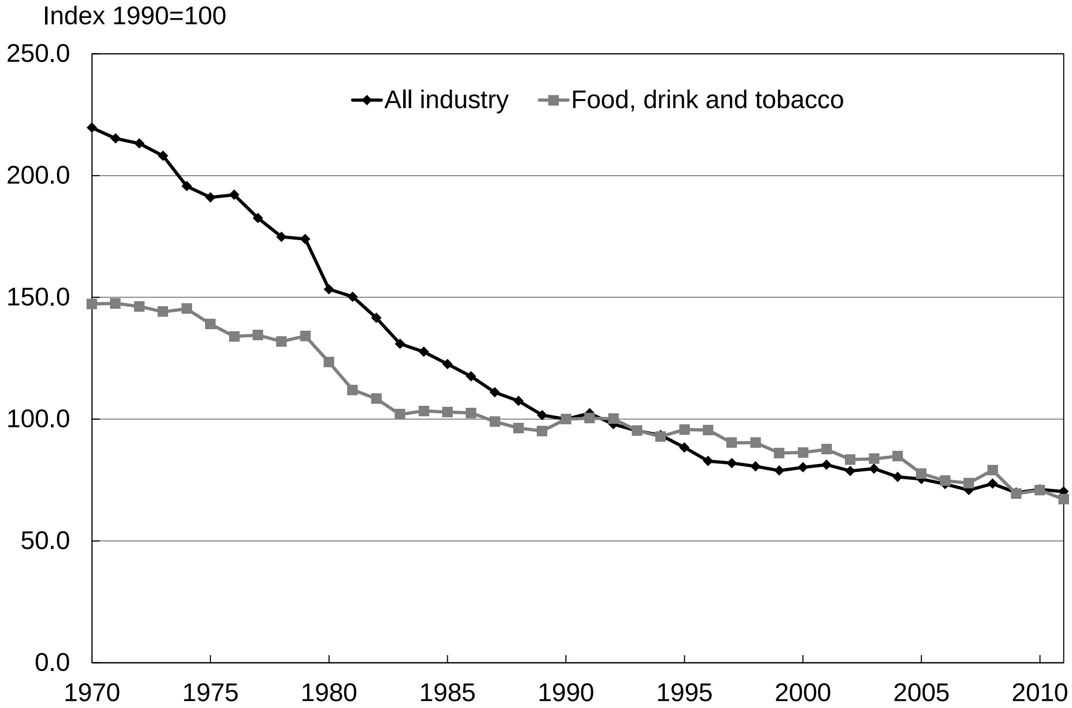

Fig. 7-5: Energy intensity index of Food, drink and tobacco; and all industry 1970-2011. Output is based on index of production, taken from ECUK (DECC 2012e).

7.1.3 Energy efficiency improvements

There were two general approaches considered in examining energy savings opportunities for the subsector. The energy use and improvement potential of large subsectors within Food and drink could be analysed in detail, in a bottom-up manner. The alternative (or complimentary) approach would be to examine the processes that use large amounts of energy within the subsector, similar to the top-down assessment of energy use in the industrial sector, as undertaken in Chapter 3. Here the second approach, concentrating on common end uses of energy was used to assess the Food and drink subsector.

There are a number of reasons this second approach was chosen. The analysis of the subsector undertaken above indicates there is no dominant subsector within Food and drink with regards to energy use. A number of subsectors would therefore have to be examined in detail to cover the majority of energy use within Food and drink. Assessments were carried out to determine whether such an approach would be feasible. It was found that within the large energy using subsectors there was substantial diversity in energy use and so detailed bottom-up studies of these subsectors would be unlikely to cover more than half the energy use within each subsector without a substantial time and resource dedication. Information on energy use within the subsectors was also not easily obtained. It is the author's experience that this is the case even at the site level. Companies themselves often have little quality information on energy use. The subsector as a whole shows a reliance on low temperature processing for much of its energy demand, with steam systems being the dominant technology in supplying this demand. This area is concentrated on in assessing the opportunities for improved efficiency within Food and drink. The baseline for this analysis is as shown in Fig. 7-3.

Cross cutting options for improving the efficiency in providing low temperature heat are examined here, namely improving the efficiency of steam systems, increasing the use of CHP and using heat pumps. Based on work from earlier in the thesis (Chapter 3 and Chapter 6) these are felt to be the technologies that show greatest potential in this regard. The majority of the current heat demand is fulfilled by steam based systems. Assuming 50% of delivered energy is used in steam systems [based on information from FDF (2008) and the US DOE (2004)] this relates to 66PJ using the data in Fig. 7-3 and comprises 72% of heat demand (including demand for both low temperature processing and for drying/ separation). The demand supplied by CHP heat is assumed to count towards the steam system demand. Direct heating therefore accounts for 26PJ, which is 19% of delivered energy. The data availability regarding end uses of energy in the subsector was generally poor. The measures therefore had to be based on information from various sources. This limited the findings regarding improvement potential to an indicative level. The assessments undertaken regarding improvements in steam systems and for increasing the use of CHP are very similar in their application to those in Chapter 3 for the whole manufacturing sector. These are therefore covered concisely and the potential through the application of heat pumps is the main focus of analysis work here.

7.1.3.1 Steam system improvement and CHP adoption

Opportunities for reducing energy use in steam systems are discussed in Chapter 3. Here the same approach to estimating potential was taken (not including the steam system demand supplied by CHP in the improvement potential). When assuming an improvement potential of 10-25% in steam systems a saving of 7-17PJ/yr was available. Assuming these steam systems are natural gas fuelled gives an emissions saving of 340-851ktCO_{2e}.

As discussed in Chapter 3 there is also an opportunity to replace this heat demand, currently fulfilled by steam systems, with CHP. This makes primary energy savings in comparison to separate steam generation and centralised electricity generation. Two studies reveal a considerable unutilised economic potential for CHP within the Food and drink sector (AEA 2000, DEFRA 2007a). An estimation of technical potential for CHP at sites included in the EU ETS is also included here, based on own calculations.

A DEFRA (2007a) study introduced in Chapter 3 calculated an economic potential for increased CHP capacity of 1033MW_e in the Food and drink sector between 2005 and 2010, representing 39.6PJ/yr of heat demand and 28.8PJ/yr of electricity demand. The actual change in CHP capacity between 2005 and 2010 was an increase in capacity of

$1MW_e$, leading to a small increase in electricity output of 0.05PJ/yr, and a decrease in heat output of 5.0PJ/yr (DECC 2012c). The economic potential estimated by DEFRA (2007a) is still therefore unrealised. Changes to the sector since the study may mean this potential has changed by a small amount. A significant potential is still expected to exist however. As a comparison the expected economic potential for CHP reported by AEA (2000), as calculated by Eurostat in 1996 was 70.1PJ/yr of heat and 39.2PJ/yr of electricity. Comparing changes in CHP output in the UK Food and drink sector between 1996 (AEA 2000) and 2005 (DECC 2010b) heat output is approximately the same whilst electricity output increased from 3.2PJ/yr to 7.5PJ/yr . The economic potential for CHP reported by AEA (2000), is therefore greater than that estimated by DEFRA (2007a). As discussed in Chapter 3 this economic potential would not likely be reached in practice due to high capital investment associated with CHP, and this is emphasised by the small increases in CHP installed between 1996 and 2005, however the high economic potentials illustrate the unutilised potential for the technology. Assessing the technical potential for CHP at those sites in the EU ETS (representing approximately 50% of total energy demand in Food and drink, see Chapter 3) in a similar manner to Chapter 3, that is based on temperature of demand and the magnitude of the demand at a site level, over 99% of heat demand would be suitable for supply by CHP, accounting for $690MW_e$. These various studies therefore indicate that there is considerable potential for CHP both at those sites included in the EU ETS, and at sites outside the scheme.

The DEFRA (2007a) assessment is felt to be the most recent and complete assessment of CHP potential available. Based on its estimation of sector wide economic potential, CHP systems could save 16.6PJ of primary energy and $854ktCO_{2e}$ of GHG emissions in comparison to an efficient natural gas boiler and CCGT electricity generation. Comparing the total outputs from CHP to Fig. 7-3 it can be seen that the application of this level of CHP (approximately 40PJ/yr of heat and 30PJ/yr of electricity) would represent significant proportions of the heat and electricity demand in the Food and drink subsector.

7.1.3.2 Increased use of heat pumps

The use of heat pumps for supplying low temperature heat to the industrial sector was introduced in Chapter 6. There was little potential for this technology under the assessment of waste heat potential undertaken in Chapter 6. This was primarily due to the methodology employed. By assessing the potential for utilising the largest waste heat resource identified at each site in the EU ETS, the potential to use smaller sources of waste heat, or the environment, as a source for heat pump use was not assessed. Previous studies of heat pump potential within the Food and drink sector were drawn on here and used to inform an analysis.

The Heat Pump & Thermal Storage Technology Centre of Japan (2010) estimated that 50% of energy currently supplied by boilers in the UK Food and drink sector could be provided by heat pumps. This was based on the assumption that temperatures of up to 100°C could be supplied by heat pumps, and 50% of steam system demand was within this range. This finding was based on studies of the Japanese Food and drink industry, and a comparison of the industry structure to the UK. This is consistent with findings of the temperature demand of heating processes within Food and drink, shown in Chapter 3 and Chapter 6. In the UK Food and drink subsector approximately 50% of final demand is for steam systems. The above methodology therefore implies that 25% of final energy demand could be supplied by heat pumps. The heat source for the heat pump technology was not specified in the study (Heat Pump & Thermal Storage Technology Centre of Japan 2010). A range of environmental and waste heat from processes would likely be used, dependent on the output temperature required and the availability of waste heat.

A study of heat pump opportunities within the French Food and drink sector (Hita et al. 2011) took a more specific approach. Using information on heat demand and heat recovery opportunities for different subsectors of Food and drink, the technical and economic potential for heat pumps that utilise other processes as the heat source, was calculated. This study of French industry (Hita et al. 2011) found the 50% share of boiler demand approach (Heat Pump & Thermal Storage Technology Centre of Japan 2010) too high. The heat recovery opportunities and heat demand did not necessarily match well in subsectors of Food and drink manufacture. The French study also assumed that a higher temperature could be reached by heat pumps (140°C, which is technically possible with waste heat acting as the source of the heat pump) (Hita et al. 2011). Although these higher temperature heat pumps are not currently economical in a lot of cases, they are expected to be close to market. This study led to the conclusion that 15% of current energy demand in the French Food and drink sector could technically be replaced by heat pumps (Hita et al. 2011). Around 30% of this identified potential was thought to be currently economical, this could well increase to 100% of the identified potential given expected future energy prices and heat pump costs (Hita et al. 2011).

A combination of the above approaches was used to assess potential for heat pumps within the UK Food and drink sector. The estimation of The Heat Pump & Thermal Storage Technology Centre of Japan (2010) was adopted as an upper limit of the heat demand that could be replaced by heat pumps. Assuming 50% of boiler heat demand could be fulfilled by heat pumps (25% of final energy demand as represented in Fig. 7-3) and that the current boilers have an efficiency of 80% would give a heat demand that could be replaced by heat pumps of 26.5PJ/yr. Using waste heat as the source for heat pumps is preferable to using environmental heat sources as higher temperatures can be reached, and higher COPs achieved (see Chapter 6). Assuming an average heat pump output temperature of 80°C, and an input temperature of 45°C, based on Hita et al. (2011), gives a COP of 4.38 [using equation (6-4) with the assumptions that there is a 5°C temperature difference between refrigerant and the source/ demand temperature, and that the actual COP is 55% of the Carnot COP]. The use of heat pumps to supply 26.5PJ/yr of heat demand would therefore require an electrical energy input of 6.6PJ/yr, and 19.9PJ/yr of low grade input heat. Possible low grade heat sources assessed here include refrigeration condensers, compressed air systems and surplus heat from heating processes (Hita et al. 2011). Table 7-1 collates the information on surplus heat available as a heat pump source. The waste heat available from refrigeration systems is based on the baseline information in Fig. 7-3 with the assumption that 245% of the input electricity is available as waste heat at the compressor (Hita et al. 2011). Compressed air use was based on DEFRA information (Market Transformation Programme 2003), with the assumption that 50% of input energy is available as waste heat (Hita et al. 2011). The total energy for thermal processes was taken from Fig. 7-3. Surplus heat from these processes at the required temperature to act as a heat pump source (30-45°C) was estimated as 15% of the input energy (Hita et al. 2011). This is a different (and additional) heat source compared to those estimated in Chapter 6, as previously higher temperature heat sources were of primary interest.

Source	Energy demand (PJ/yr)	Energy available as surplus heat for heat pump source (PJ/yr)
Refrigeration	11.1	27.3
Compressed air	1.4	0.7
Thermal processes	91.9	13.8
Total		**41.8**

Table 7-1: Surplus heat available as a source for heat pumps in the Food and drink subsector.

The above analysis indicates that there is a large enough resource of recoverable heat to supply heat pumps in fulfilling 25% of final energy demand. However, as previously found in the French Food and drink sector (Hita et al. 2011), the supplies of this heat and the demand for heat pumps are not necessarily co-located. With these considerations an estimate of 5-25% of final energy demand being supplied by heat pumps is adopted. The lower end is likely currently economic [based on savings identified in a study of the French Food and drink subsector (Hita et al. 2011)] whilst the upper limit may become possible with developments in heat pump technology over the next decade and possibly utilising heat pumps that use the environment, rather than waste heat, as a heat source. As information on the UK Food and drink sector was not available to the same disaggregation as its French counterpart, as used in the study by Hita et al. (2011), the assessment of the potential for applying heat pump technology using waste heat sources was necessarily more indicative. Significant opportunities for heat pump use within the Food and drink sector have been reported in the Meat subsector (Fritzson and Berntsson 2006) and Dairy subsector (Carbon Trust 2010c) in addition to those in the Distilling subsector discussed in Chapter 6.

The primary energy and carbon savings offered by heat pumps are dependent on the method of electricity generation and the alternative heating technology. Assuming a system operating with the COP specified above, replaces a natural gas fuelled boiler with an efficiency of 80%, and is supplied by grid electricity, with emissions factors as discussed in Chapter 2, means that for every PJ of heat demand supplied by heat pumps in preference to natural gas boilers 31ktCO_{2e} are saved, final energy savings would be 1.02PJ and primary energy savings would be 0.66PJ. With 5-25% of final energy demand suitable for replacement by heat pumps this represents 6.6-33.1PJ/yr of final energy demand, or 5.3-26.5PJ/yr of heat demand. Replacing this demand with heat pumps has the potential to save 5.4-27.1PJ/yr of final energy demand, 3.5-17.4PJ/yr of primary energy demand, or 166-829 $ktCO_{2e}$. Supplying the electricity from a renewable source with an assumed zero emission factor would save approximately double the amount of emissions (65$ktCO_{2e}$/PJ). If the boiler being replaced was supplied by biomass, or steam was originally supplied by a CHP system then savings would be less. The economics of a heat pump installation depend on the capital cost of the system and the price of electricity (assuming an electrically driven system), compared to the existing fuel (often natural gas, as used for the calculations above). Heat pumps therefore benefit from a low 'spark gap', in contrast to CHP plants (see Chapter 3 for further discussion of the spark gap). The Renewable Heat Incentive (RHI) in the UK can help fund heat pumps, although it is currently limited to ground and water source installations (DECC 2011e). There has been some criticism regarding the lack of support for surplus heat recovery within the RHI (Hubert 2010).

7.1.4 Discussion

The options discussed here all focus on supplying low temperature heat, they can therefore not be used together to supply the same heat demand. Some of the efficiency savings applied to steam systems (rather than the boiler plant) would also be applicable if a CHP plant, or heat pump, replaced the boiler in heat generation. Overall energy and emission savings from each of the options considered are similar, as shown in Fig. 7-6. In the near term it might be expected that steam system efficiency improvements are pursued where economic, as they require little disruption or capital costs. With the existence of capital, fossil fuelled CHP may also be expected to increase in the near term. Over the longer term heat pumps may increase in use, especially if the temperature range that can be supplied increases, electricity is decarbonised, and costs reduced with wider adoption. The longer term may also see the use of non-fossil fuelled CHP systems increase.

The approach used here to estimate savings through the technology options can simply be applied to other sectors with knowledge of steam system and low temperature energy demand. The broad nature of such an approach does lead to considerable uncertainty, but is useful in indicating where the most substantial savings may be seen.

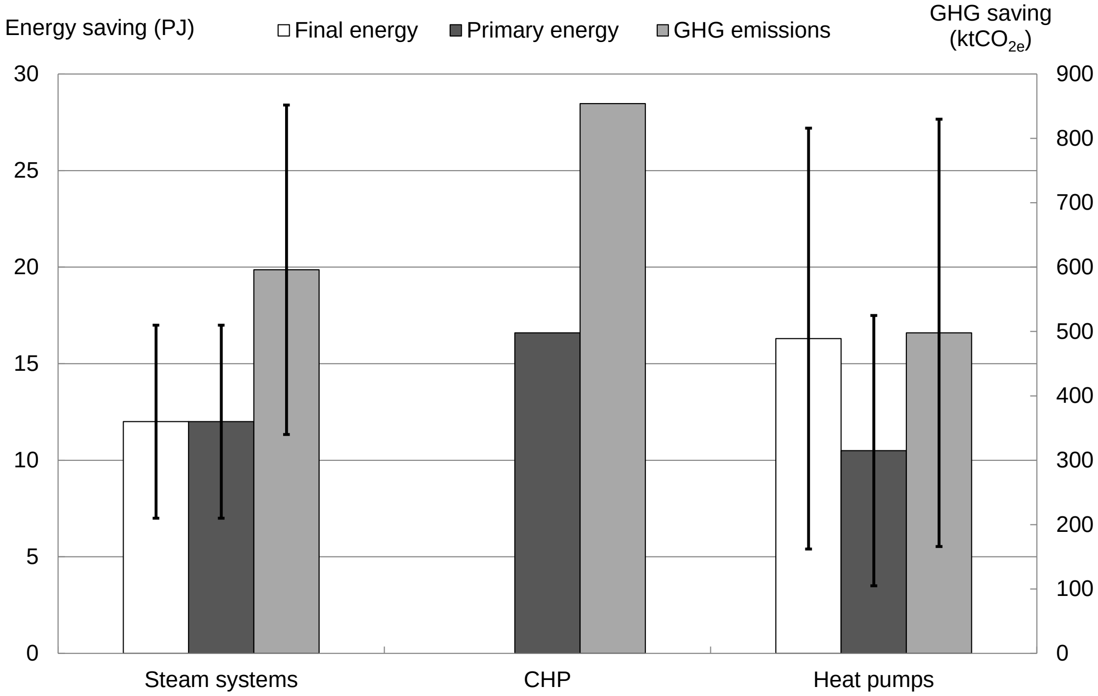

Fig. 7-6: Annual energy and emission saving through low temperature technologies in the UK Food and drink sector.

Cross cutting technologies that were not examined here include improvements to motor systems (incorporating refrigeration and compressed air); lighting; and space heating (although space heating has some common ground with the discussion of low temperature heating here). The opportunities for improving efficiency in motor systems were discussed in Chapter 3, a similar approach could be taken to the Food and drink sector. CCS and heat recovery opportunities are also to some extent cross-cutting technologies. CCS is unlikely to find applications within Food and drink as there are not sufficient levels of emissions per site for the technology to be considered. Heat recovery opportunities have been covered in Chapter 6. The heat recovery opportunities within Food and drink manufacturing were not covered fully in this assessment however, only focussing on sites included in the EU ETS. There is thought to be potential for saving 8PJ/yr through heat recovery throughout the subsector (Reay 2008). As much of Food and drink has demands for heating and cooling the use of process integration (on bigger, more complex sites) may show potential (AEA 2000). A study of EU wide energy saving opportunities (AEA 2000) found the biggest cost effective savings within Food and drink to be CHP and energy management measures. The Energy Efficiency Best Practice Programme in the UK suggested 40% of Food and drink manufacturing does not practice energy management and this has potential savings of 9% of energy at those sites, this represents 4.8PJ/yr of final energy saving, using information in Fig. 7-3.

7.2 THE CEMENT SUBSECTOR

In contrast to the Food and drink subsector the Cement subsector is very homogeneous in its output, it is essentially a single, sequential process route with a single product. The vast majority of cement manufacture in the UK is of the form 'calcium silicate', more commonly referred to as ordinary Portland cement (OPC). Almost all cement is manufactured for use as concrete for construction purposes.

In this section the current energy use and emissions within the UK Cement industry are analysed. A decomposition analysis is then used to examine the changes in the energy demand of UK cement kilns since the 1970s and the underlying causes of these changes in demand. The thermodynamic performance of a cement kiln is discussed with attention paid to the remaining improvement potential. Options for improving the efficiency of the sector through switching kiln technology to best available technology (BAT), recovering heat to generate electrical power, and by substituting clinker with alternatives are assessed. These efficiency options are discussed and compared to longer term options for reducing the emissions from UK cement manufacture.

7.2.1 Current energy use

The manufacturing steps of the dry process of OPC production are shown in Fig. 7-7, this is the most commonly used process route in the UK and is also the most efficient option, where there are small differences in alternative process routes they are described later in the current section. In the dry process route of cement manufacture a form of calcium carbonate (usually limestone) is quarried and delivered to the plant (these steps are not included in the definition of cement manufacturing here). The first stage of manufacture at the plant is the crushing, grinding and preparation of raw materials (including drying). Small quantities of other minerals, in addition to the calcium carbonate source may be added to get the composition of the raw material mixture correct (Choate 2003), this usually includes clay and sand (IEA 2009). The raw material may then go through a number of stages of preheating and sometimes a precalciner, both of these steps act to improve the efficiency of the plant by utilising surplus process heat and are discussed in more detail below. The raw material is then fed into the rotary kiln, where calcining occurs (assuming calcining has not been completed in a precalciner). During calcining calcium carbonate decomposes into calcium oxide and carbon dioxide at approximately 900°C (European Commission 2010b). The calcium oxide is then sintered, it reacts with the other materials present, at approximately 1500°C to form small nodules known as 'clinker' (European Commission 2010b), this clinker is the output of the kiln. After exit from the kiln the clinker is then cooled and milled with gypsum, and possibly other materials, to form cement (Choate 2003).

On-site energy demand is dominated by the kiln system (including the precalciner if fitted), which is primarily fuelled by coal in the UK. Around 93% of final energy demand in cement manufacture is for fuelling the kiln (Choate 2003). There are also considerable process (non-energy-related) emissions from the kiln, representing 60% of its carbon dioxide emissions (CSI and ECRA 2009). The kiln therefore forms an obvious focal point for analysis work, dominating both energy demand and emissions.

Additional energy use in cement manufacture is mainly electrical, primarily for the grinding and milling processes (Choate 2003). Indirect emissions from electricity demand add approximately 10% to the emissions from the rest of the process (CSI and ECRA 2009).

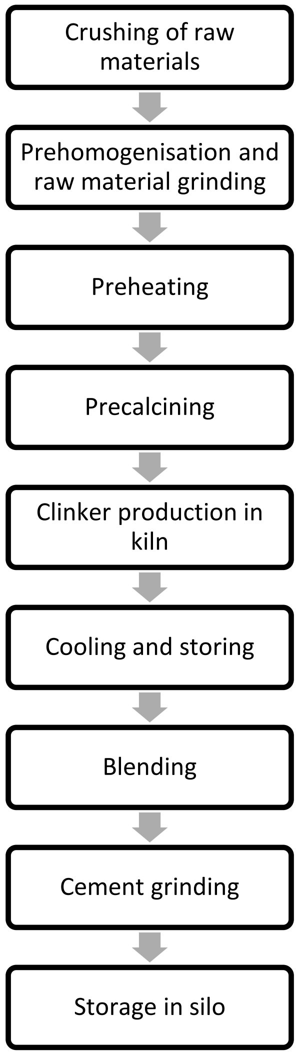

Fig. 7-7: Stages of cement production. The dry production route utilising both preheating and precalcining is represented.

Preheaters and precalciners are an important part of the modern cement plant. Preheaters use heat from the kiln to preheat the raw materials before they enter the kin, so reducing the energy requirement of the kiln. The number of stages of pre-heating that can be used depend on the raw material composition (IEA 2009). Air exiting from the preheaters can be used to dry the raw materials if required, and this will limit the number of preheating stages to four or five (three in rare instances). Up to six stages of preheating can be used with a dry raw material source (European Commission 2010a). The calcination process generally starts to occur in the preheaters, when a high enough temperature is reached. This process can be extended with a precalciner where fuel is also burnt in a secondary combustion chamber with preheating air (IEA 2009). If only air from the kiln passes into the precalciner, the amount of fuel that can be burnt in the precalciner is limited to around 25% of the total demand for the kiln and precalciner

(Moore 2011). The amount of fuel burnt can be increased to 70%, if air from the cooler is also used to supply the precalciner (Moore 2011). A schematic of a system using preheating and a precalciner supplied with air from the kiln and cooler is shown in Fig. 7-8 (this is one of many possible arrangements). In the case of a precalciner supplied with air from the cooler the raw materials can be completely calcined before entering the kiln, which then only acts to sinter the material [the rotating action of the kiln is important for the sintering process (Moore 2011)]. One advantage to such a layout is that a relatively short kiln is required, meaning a larger output can be achieved for a given size of kiln.

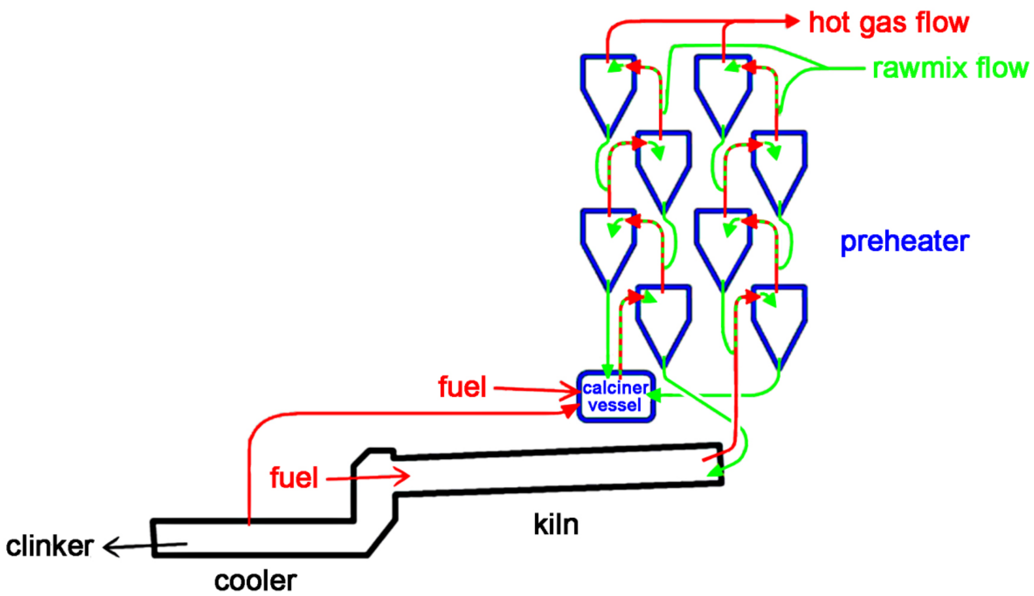

Fig. 7-8: Layout of a four-stage air-separate precalciner kiln, taken from Moore (2011), and reproduced with permission.

There are small variations in the basic process route described above, these are the wet, semi-wet, and semi-dry process. The kiln and precalciner (if used) dominate energy use independent of the process. Historically the wet process route offered the main alternative to the dry process route. The wet process adds water to the raw materials to form a slurry, and is required with some raw material sources. The wet slurry is more easily ground than dry materials, but requires more energy in order to evaporate the water later in the production process (Choate 2003). The semi-wet process removes part of the water content of the slurry through filtering, and is therefore more energy efficient than the wet process (Moore 2011). In the semi-dry process water is added to dry raw materials to form pellets (Moore 2011), this allows grate preheaters to be used (in comparison to the gas-suspension preheaters used in the dry process). The UK currently (as of the end of 2011) has fourteen cement kilns located at twelve sites, four kilns having closed during the period 2008-9 (Edwards 2011). There are eleven dry kilns (representing 76% of capacity), three semi-dry kilns (representing 11% of capacity) and a single semi-wet kiln (representing 13% of capacity) (Edwards 2011). The overall SEC of the kilns in the UK is 3.8GJ/tonne clinker, this includes energy used in start-up and shut-down operations, instantaneous energy efficiency would be higher (CSI 2012, Edwards 2011). Current best available technology (BAT) of the cement kiln is the dry process route utilising four to six-stages of preheating and precalcining as described above, this gives a SEC of 2.9-3.3 GJ/t (European Commission 2010a), the variation in the SEC is due to differences in raw materials and so the number of stages of preheating (as discussed above). All dry kilns in the UK have four- or five-stage preheating, the majority also employ precalciners (Edwards 2011) [precalciners are not confined to the dry process (Moore 2011)].

In 2010 the UK cement subsector used 26.1PJ of thermal energy, 61% of which was supplied by coal with the remainder supplied by waste fuels (Edwards 2011), the subsector also used 3.9PJ of electricity (CSI 2012). This represents 34.6PJ primary energy and 6.5MtCO_2 emissions (including emissions from electricity used, but not including biomass combustion), 3.79MtCO_2 (58%) of these emissions were non-energy-related process emissions (DECC 2012k). Production for 2010 was 9.4Mt of cement from 6.9Mt of clinker (CSI 2012). These values have decreased substantially since a few years previous due to plant closures and the general economic slowdown. Between 2000 and 2007 emissions were over 10MtCO_2/yr and cement production over 14Mt (CSI 2012) , in 2010 the sector ran at just 61% of capacity [own calculations based on capacities reported by (Moore 2011)]). In the case of the Cement subsector it was found that good quality data could be obtained from the trade association (Edwards 2011), and similar organisations (CSI 2012), as well as at the site level (Moore 2011). This was as energy use is a high priority in the subsector, and as the product route is well-defined data of this type is relatively easily collated.

7.2.2 Decomposition analysis

Examining the historical improvement in energy use of UK cement kilns can inform an analysis of future opportunities. Energy use in UK kilns has dropped by approximately 60TJ between 1973 and 2010 (Moore 2011). This represents a fall of 65% in the level of energy demand since 1973, a considerable reduction. A decomposition analysis was used here to separate the different effects contributing to the change in energy demand, these effects were:

- Clinker output
- Switching between dry, semi-dry, semi-wet and wet kiln technologies (the structural effect)
- Specific energy consumption (SEC) improvement of the different kiln technologies

A Log Mean Divisia Index (LMDI I) methodology was used for the decomposition analysis as discussed in Chapter 5. Information on the physical output, and SEC of kilns in the UK between 1973 and 2010 was extracted from an online source of information on individual kilns (Moore 2011) and aggregated to represent the UK situation. Whilst this may not accurately represent year-to-year fluctuations in production it should capture trends well, and is sufficient for the current analysis. The results of the decomposition analysis are presented in Fig. 7-9. It can be seen that over all time periods the effect of improvements in SEC of the different kiln types (leading to a reduction in energy demand) is the smallest component of the falling energy demand. The overall sector

SEC for clinker production improved 37% between 1973 and 2010, but this was mostly caused by changing production away from wet kilns, rather than improvements in the energy efficiency of the different kiln types. In the most recent time period (2000-2010) the effect of improvements in SEC of the kilns has been substantially smaller than any previous period. This could indicate that the limits of efficiency of the kiln are being reached. Fig. 7-9 shows that switching to more efficient kiln types (the structural effect) has had a substantial effect in the reduction seen in energy demand. However, now that dry kilns dominate UK production, further potential for reducing energy demand in this manner is limited. Over the whole time period studied here (1973-2010) there has been a falling demand in clinker, and this has had the greatest effect in reducing energy demand. This fall in clinker output can be the result of either a reduction in the output of cement, or due to the substitution of clinker in cement manufacture with less intensive alternatives. Similarly a fall in cement demand can be caused by a reduction in concrete demand, or an increase of cement substitution by alternatives, which would affect clinker output.

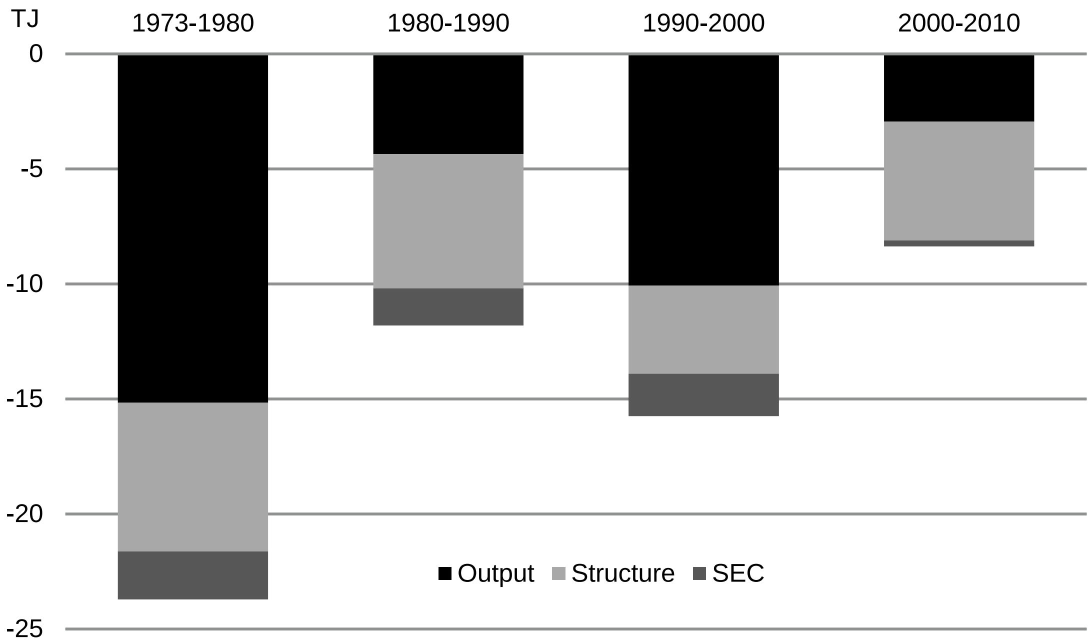

Fig. 7-9: Decomposition of UK kiln energy use 1973-2010, the effects of changes in structure, output and SEC are separated.

Cement production peaked in the UK in 1973 (Moore 2011), the subsequent decline is represented in the decomposition analysis here. There is often a link between the economic development of a country and its cement production. Most of cement manufactured in used to produce concrete, which is used for construction. As infrastructure and buildings are rapidly built during industrial growth demand for cement grows (as is currently occurring in China and India). After this initial boom in cement manufacture the demand declines, as the rate of construction also declines. The peak of cement production usually occurs when GDP is $10-15,000 per capita (Allwood and Cullen 2011). In 1973 UK GDP per capita was approximately $14,000 (Trading Economics 2013), in concurrence with this relationship. Cement, and hence clinker, demand is driven by domestic construction as international trade in cement is not common. The low relative cost of cement makes it uneconomic to transport more than 200-300km by land (European Commission 2010b), although a seaport or rail link located near the plant can increase this. Imports and exports of cement are therefore low. There is however still some concern surrounding 'carbon leakage' due to the carbon-intensive nature of cement manufacture. To prevent this The Carbon Trust recommended a taxation of imports based on the best available technology for producing cement (Carbon Trust 2010e). This would be possible due to the homogeneous nature of cement. It is therefore likely that significant cement manufacture will continue in the UK for the foreseeable future, and will be linked to the growth of the domestic construction industry.

7.2.3 Thermodynamic assessment

The minimum theoretical thermal energy demand required in the production of clinker is 1.65-1.8GJ/t (CSI and ECRA 2009). Additional energy is required for drying the raw material, this increases the theoretical minimum energy demand to 1.85-2.8 GJ/t (CSI and ECRA 2009), and is dependent on the moisture content of the raw material. Energy and exergy analyses can indicate those areas of the process that are responsible for inefficiencies, which losses can be reduced, and so how the thermodynamic potential can be approached.

Khurana et al. (2002) analysed an Indian cement plant with a five-stage preheater and inline precalciner. The plant required energy inputs of 3.7GJ/t clinker and 0.31GJ electricity/t cement. A thermodynamic analysis of the kiln system including the preheater, precalciner, kiln and cooler was undertaken. A Sankey diagram showing the flows of energy in the system investigated is shown in Fig. 7-10, the values shown are a percentage of the energy released from the combustion of coal, both within the kiln and the precalciner. The plant represents a high level of surplus heat reuse, recovering flows from both the kiln and cooler. The primary efficiency of the plant was found to be 50%. 15% of the energy input was lost in the output streams, mainly due to radiation and dust, this would be difficult to reduce. The remaining 35% of energy input lost was in hot streams. There were found to be three main hot flows out of the process, the hot clinker, the preheater exhaust and hot air from the cooler. Information on these flows is summarised in Table 7-2. The thermomechanical exergy shown is based on calculations undertaken based solely on the temperature of the flow, with a dead state temperature of 25°C. This indicates the potential of the heat in the flows in producing work. Recovering heat from the solid clinker would be difficult, and also represents the smallest potential source of energy and exergy (see Table 7-2). Both the preheater exhaust and hot air from the cooler could hold potential for recovery. The preheater exhaust represents the highest enthalpy stream, but due to its higher temperature the hot air from the cooler represents a higher source of exergy. Opportunities for utilising these streams are discussed in section 7.2.4.2 below.

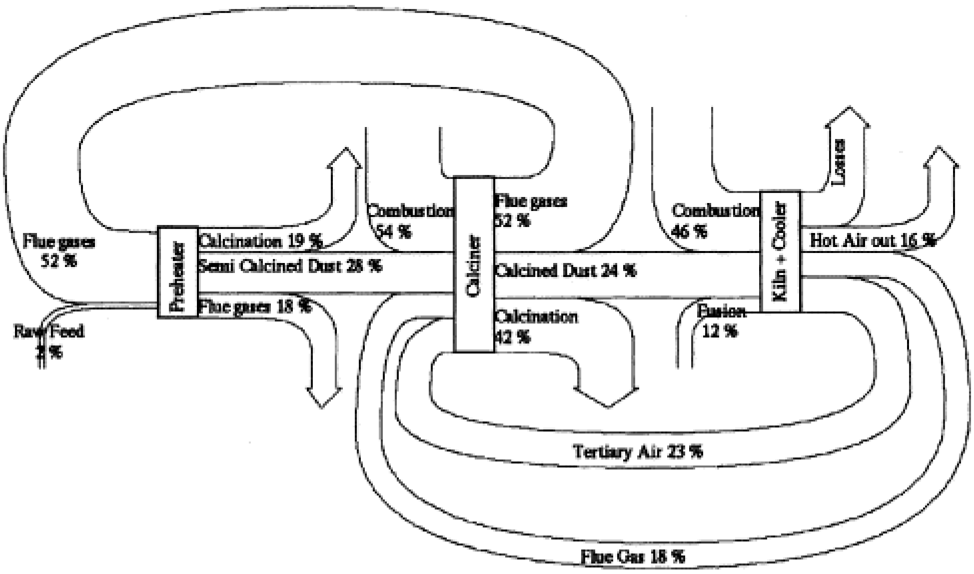

Fig. 7-10: Sankey diagram of preheater, calciner, kiln and cooler, taken from Khurana et al. (2002) and reproduced with permission (copyright Elsevier).

Stream	Flow rate (kg/kg clinker)	Specific heat (kJ/kg K)	Temperature (°C)	Enthalpy (kJ/kg clinker)	Exergy (kJ/kg clinker)
Clinker	1.00	0.8	100	82	16.5
Preheater exhaust	2.27	1.0	280	636	293.2
Hot air from cooler	1.42	1.0	400	568	316.2

Table 7-2: Hot output stream from cement kiln system, information from Khurana et al. (2002), exergy based on own calculations.

7.2.4 Energy efficiency improvements

The decomposition analysis above indicates that the limits of technical efficiency in the current clinker production process may be being reached. The assessment of energy efficiency improvements here looks at a number of options that may still hold potential. Switching all production to best practice technology; reusing waste heat from the kiln system to produce electrical power; and methods to reduce clinker demand, whilst still producing OPC, are examined. Other possibilities for long-term reduction in energy use and/ or emissions are fuel switching, the use of CCS, and the use of alternative materials to provide the same service as OPC. These longer-term opportunities are considered to be outside the scope of the thesis but are discussed briefly as they are potentially important opportunities for the subsector, and help give context to the energy efficiency improvements. The 2010 values of energy demand and production discussed above are taken as the baseline for assessing improvement potentials.

7.2.4.1 Switch to Best Available Technology (BAT)

Table 7-3 examines the improvement potential through upgrading existing kilns in the UK to best available technology (BAT), defined above to be a four to six stage preheated kiln with a precalciner, giving a SEC of 2.9-3.3GJ/t clinker. The achievable level of performance would be dependent on the raw material composition, for this reason the range of values is used here to represent BAT. Without examining the raw materials in detail it would not be possible to define where in this range the potential lies. Table 7-3 shows the existing capacity and SEC of the technologies, taken from Moore (2011), and expected savings in energy demand and emissions from switching to BAT. Percentages shown relate to the existing technology baseline. Where the SEC varies between kilns using the same technology the SEC calculated for the technology is weighted by the capacity of the individual kilns. It is assumed that all kilns run with an equal capacity factor. The baseline SEC for the sector shown in Table 7-3 is 3.66GJ/ t clinker. This is lower than that reported by the trade association of 3.8GJ/ t clinker (Edwards 2011) with the difference likely being due to the low capacity (61%) in the base year affecting the realised SEC. The increase in SEC of a kiln due to running at reduced capacity is estimated to be 0.1-0.2GJ/t clinker (CSI and ECRA 2009, European Commission 2010b), this therefore corresponds with the discrepancy in reported values.

Existing technology	Weighted SEC (GJ/t)	Capacity (Mt clinker/ yr)	Energy demand reduction available through adopting BAT (PJ)	Emissions reduction through adopting BAT (ktCO_2)
SW 2st-PC	4.60	1.46	1.16-1.51 (3.85-5.03%)	87-114 (1.35-1.76%)
SD Lepol grate	3.60	1.30	0.24-0.55 (0.79-1.85%)	18-42 (0.28-0.65%)
Dry 4st	3.65	2.30	0.50-1.06 (1.65-3.51%)	37-80 (0.58-1.23%)
Dry 4st-PC	3.61	3.06	0.58-1.32 (1.93-4.41%)	44-100 (0.67-1.54%)
Dry 5st-PC	3.31	3.20	0.02-0.80 (0.06-2.66%)	1-60 (0.02-0.93%)
Total	**3.66**	**11.32**	**2.49-5.24 (8.3-17.5%)**	**188-397 (2.9-6.1%)**

Table 7-3: Savings potential in the UK Cement sector through a switch to BAT. SW: semi-wet, SD: semi-dry, st: preheating stages, PC: pre-calciner.

The total savings in relative emissions shown in Table 7-3 are significantly lower than the relative reductions in energy demand. This illustrates the importance of process emissions in the Cement sector, which are not affected by the changes in kiln efficiency. For comparison to the efficiency savings shown in Table 7-3 if the sector ran at the theoretical minimum energy demand of 1.85-2.8GJ/ t clinker identified above the savings would be 19.8-41.6% of energy demand and 6.9-14.5% of emissions.

The greatest potential savings seen for a given technology are in switching the semi-wet kiln to BAT. Rather surprisingly the semi-dry kilns operate with marginally greater efficiency than dry kilns with four-stage preheaters and four-stage preheaters and precalciners. The dry kilns with five–stage preheating and precalciners show the smallest relative potential savings as expected. The likelihood of realising a significant part of the potential shown in Table 7-3 is questionable. The capital investment required for a new kiln is generally very high in relation to the fuel savings it would bring (European Commission 2010b); this is especially true in the absence of any wet kilns to displace. Replacement may be economically justifiable only if it brings additional capacity (Langley 1984). However, as the subsector is running at just 61% of capacity this is unlikely to be attractive until the retirement of significant old capacity is coupled with firm projections of increased demand from the domestic construction industry. The age of the current kilns and the availability of raw materials are important considerations when determining the ability of kilns to change the technology they utilise. For example the semi-wet kiln operating in the UK is relatively new, having been constructed in 2000 (Moore 2011) and is unlikely to be replaced in the near-term. In terms of additions to existing kilns adding a precalciner is generally a more viable option than increasing the number of stages of preheating. Adding stages of preheating may be constrained by the raw materials used as heat may be required for their drying. Retrofitting a preheater stage to a pre-existing kiln also has large cost implications (Institute for Industrial Productivity 2012). The addition of a precalciner, in addition to improving efficiency, can increase the capacity of a kiln and payback is generally less than five years (Worrell et al. 2008). Adding a precalciner to an existing kiln would represent only a small improvement potential for the sector, only being applicable to four dry kilns with four-stage preheating. Three of these four kilns were built in the 1970s (Moore 2011) and would be expected to be reaching the end of life, it may therefore be difficult to recoup any investments in improved efficiency, however if they are rebuilt it would be hoped BAT would be employed.

Some of the kilns in the UK are performing poorly compared with the expected performance given the technology employed. There may be some opportunity for improving efficiency with more minor changes, these could include reducing heat losses, process control and optimisation, and combustion system improvements (Institute for Industrial Productivity 2012). The effect of such changes would be included in the estimations of improvement potential shown in Table 7-3, and although less significant in terms of energy savings, would be more likely to be realised. An emerging technology that could replace dry kilns in the future to produce OPC is the fluidised bed kiln, which is currently at the demonstration stage of development. Savings of 0.42GJ/t clinker are reported in comparison to a dry kiln operating at 3.4GJ/t clinker, this is coupled with increased electricity demand of 0.03GJ/t clinker (NEDO 2006).

7.2.4.2 Heat recovery for power generation

Cement manufacturing is a heat-intensive process, there is a substantial amount of waste heat recovery employed in the preheating and precalcining of the materials before entering the kiln. The analysis of Khurana et al. (2002) discussed above highlighted hot streams that arise after preheating and precalcining are employed. This streams may hold potential for further recovery. Opportunities for using this heat to generate power have been identified by a number of studies (European Commission 2010b, Institute for

Industrial Productivity 2012, Khurana et al. 2002, NEDO 2008, Worrell et al. 2008). Using waste heat to generate power was also highlighted as the primary opportunity for increasing heat recovery in the Cement subsector in the analysis of Chapter 6. Table 7-4 summarises information from a number of sources on these opportunities. These opportunities cover both ORC and traditional steam cycle systems, dependent on the site size and temperature available (see Chapter 6 for further discussion on the different recovery technologies). The temperature available as surplus heat is dependent on the technology employed in the kiln. For example in the information shown in Table 7-4 the preheater exhaust recovery temperature is higher in the reference plant for NEDO (2008) in comparison to Khurana et al. (2002) due to using a four-stage preheating process rather than a five-stage process. NEDO (2008) confirms a preheater exhaust temperature of approximately 250°C for a five-stage preheater exhaust.

Reference	Source of heat	Temperature of heat (°C)	Electrical output (kJ/kg clinker)	Payback time (years)
Khurana et al. (2002)	Preheater exhaust	280	100	2
	Cooler hot air	400		
NEDO (2008)	Preheater exhaust	350-380	135*	2.7-3.2
	Cooler hot air	200-250		
Institute for Industrial Productivity (2012)	Preheater exhaust	N/A	72-162	Less than 3
	Cooler hot air	N/A		
Chapter 6	Cooler exhaust air	150	39-84#	-

Table 7-4: Reported waste heat to power opportunities in the cement subsector. *Based on calculations using the 2010 UK ratio of clinker to cement (CSI 2012). #Based on calculations of the mean output of clinker 2000-2005 (CSI 2012).

Considering the variation between kiln technologies the studies referenced in Table 7-4 are generally in good agreement regarding the electrical output and payback time for projects. Comparing the findings of Chapter 6 with the other studies in Table 7-4 reaffirms the conservative nature of the waste heat work, but also shows it to have given a reasonable approximation of more focussed work.

It needs to be ensured that when installing such a heat recovery system it does not adversely impact the plant's other operations. For those studies for which information is available [Khurana et al. (2002) and Chapter 6] the hot streams from which heat is recovered are kept above their dew point, with only the sensible heat recovered, condensation in the heat exchanger should therefore not be an issue. The cooler is the most widely used source of waste heat, the large amount of dust present in the preheater exhaust means heat recovery is difficult (European Commission 2010b). High levels of filtering may be required to utilise the preheater exhaust, or downtime for cleaning may be required (Khurana et al. 2002), which should be factored into costs (this is an example of a hidden cost as discussed in Chapter 4). As discussed in Chapter 6 the recovery of waste heat is essentially the exploiting of an inefficiency. More surplus heat may therefore arise from less efficient plants but in many cases it is preferable from a thermodynamic perspective to first reduce this heat from improving efficiency before waste heat-to-power technologies are utilised. In practice, as discussed above, the economics may not be attractive for the efficiency to be improved however. In the case of highly efficient preheating systems and coolers reusing heat to produce power may not be possible, at least not economically (European Commission 2010b). The payback times quoted in Table 7-4 will also be dependent on the local electricity price. As an alternative to utilising the heat arising from the cement plant in heat-to-power technology it can be used to supply district heating if a suitable opportunity exists in the locality (European Commission 2010b).

If heat-to-power technology was adopted throughout the UK sector at a rate of 50-150kJ/kg clinker this would produce 0.34-1.03PJ of electricity (0.90-2.69PJ as a primary equivalent), representing 9-26% of the Cement subsector's electrical demand in 2010 and saving 49-148ktCO_2 (assuming the electricity would have been grid supplied), this represents 0.8-2.3% of sector emissions.

7.2.4.3 Clinker substitution

The manufacture of clinker is the most energy, and emissions, intensive stage of cement manufacturing. Cement production involves the milling of clinker with other materials to produce the final cement. If the proportion of non-clinker in cement manufacture can be increased (whilst not compromising the product) this can reduce the energy and emissions associated with manufacturing each unit of cement, therefore increasing the efficiency of the cement manufacture. Suitable non-clinker material includes ground granulated blast furnace slag (GGBS, a by-product of iron manufacture) and pulverized fly ash (PFA, a by-product from coal fired power stations). Around 15% of cement supplied to standard EN197 part 1 in the UK is non-clinker (Edwards 2011). In the UK cement is primarily manufactured with relatively high clinker contents. When cement is used in concrete production increased substitution occurs. This approach is different to much of Europe, where more clinker substitution occurs during cement manufacture. In 2010 the proportion of additional cementitious material (mainly GGBS and PFA) in concrete production was 28% of total cementitious materials (Sustainable Concrete Forum 2012), this represents the full level of clinker substitution. The UK approach of substituting when manufacturing concrete has two advantages, the GGBS and PFA do not need transporting further than required, and the concrete producer can optimise the mix to the construction requirement (Edwards 2011). The substitution of clinker is dependent both on the availability of alternative materials, the quality of such materials, and cement/ concrete specifications, excessive clinker substitution could adversely affect the quality of cement and concrete. The main substitutes in the UK rely on carbon-intensive industries, iron manufacture and coal-fuelled power production. Whether these industries continue in the UK and can supply a high level of quality clinker substitutes is dependent on future carbon targets and technology developments. The upper limit of clinker substitution is therefore difficult to estimate, here an assumption of increasing to 40% substitution, from the current level of 28% is adopted. This is technically possible, yet ambitious, the current target of the Sustainable Concrete Forum is around 33% (Sustainable Concrete Forum 2012). The exact savings offered in energy demand and emissions are dependent on the precise mix of substitutes, for example if substituting with PFA electricity is required for blending, but not grinding, meaning electricity demand is lower compared to clinker production (CSI and ECRA 2009). In contrast substituting GGBS requires almost no change in electricity demand (blending and grinding requirements being similar to those for clinker) and the reduction in thermal energy demand in clinker production is offset slightly by thermal energy demand for drying GGBS (CSI and ECRA 2009). Here the savings presented are due to the savings of thermal energy demand and process emissions in the saved clinker production, using 2010 base year values. No allowance is made for the net energy demand of clinker alternatives in comparison to clinker. The energy savings through this increase in clinker substitution from 28-40% would equal 4.1PJ (13.8% of 2010 sector energy demand) and emissions saving would be 0.94MtCO_2 (14.4% of 2010 sector emissions). These calculations assume sector averages of kiln SEC and process emissions.

7.2.5 Discussion

Fig. 7-11 compares the energy and emissions savings through the efficiency measures discussed above. The increased level of clinker substitution shows the greatest savings in both energy and emissions. Higher levels of clinker substitution could also be considered the most likely realised of the options. Kiln efficiency improvements may be limited, as discussed above, although it is hoped some of the identified potential is realistic. Heat-to-power technology has not yet been widely employed, whereas clinker substitution is a well-established technique which has been increasing in its application (CSI 2010). There are no error bars shown for clinker substitution in Fig. 7-11, as there are for other options. The result shown represents the maximum level of substitution likely to be realised.

The options shown in Fig. 7-11 are not synergistic. If efficiency improves or clinker substitution increases (lowering kiln output) heat-to-power opportunities will be smaller. With a more efficient kiln the effect of clinker substitution will be less, and similarly increased clinker substitution will limit the absolute improvements seen from efficiency increases.

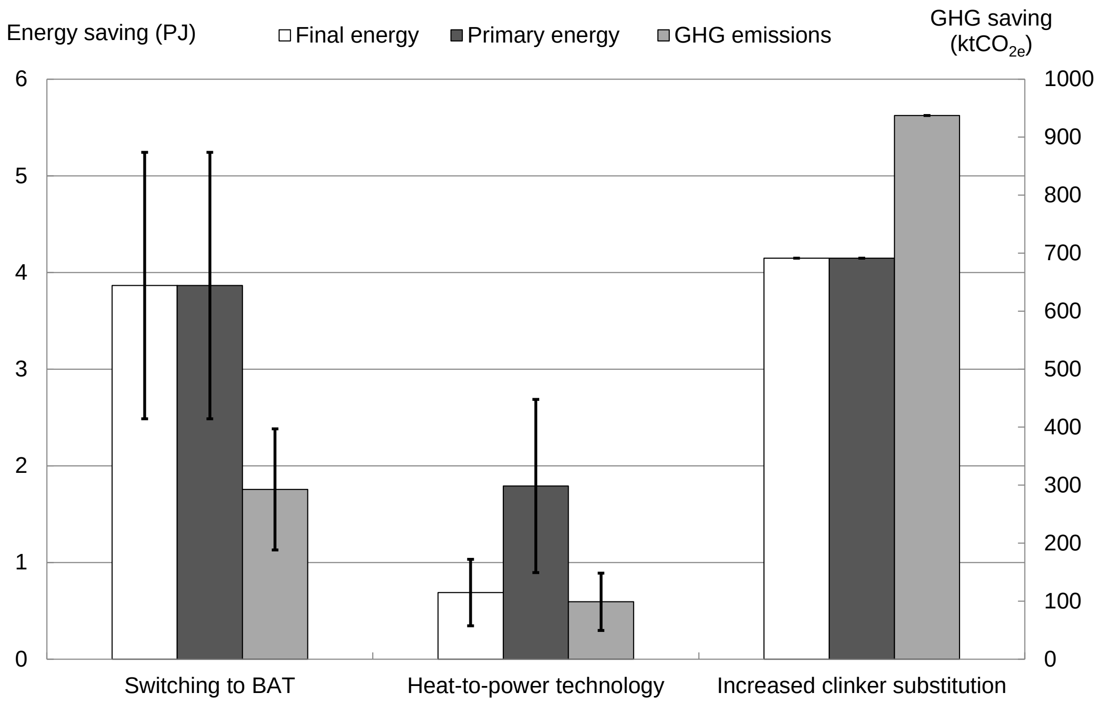

Fig. 7-11: Energy and emissions saving through applying improvement potential options to the UK Cement subsector.

The effect of fuel switching, CCS and alternative cements on the subsector's emissions levels may be greater than the options considered above, and may also negate the effect of the above improvements. Of the non-efficiency options discussed here fuel switching has the potential for immediate impacts, whereas CCS and alternative cements are more speculative technologies and available on longer timescales. The options are each discussed briefly here.

Coal currently dominates fuel use in UK kilns. Of the remainder 38% of thermal energy for the kiln is through waste derived fuels, 17% of this waste is biomass (Edwards 2011). Switching from coal to natural gas is possible but unlikely as it is not economically viable in the UK (CSI and ECRA 2009). The cement kiln can run on 100% waste fuel as long as minimum calorific values are met (CSI and ECRA 2009), this is more easily achieved if a precalciner is used, therefore being synergistic with efficiency improvements. Increasing biomass use is difficult, due to the limited supply and increased competition for the resource, particularly from power generators, where increased costs can more easily be passed onto consumers (Edwards 2011). Increasing non-biomass waste offers smaller carbon savings, although alternative waste fuels can be 20-25% less carbon intensive in terms of direct emissions when compared to solid fossil fuels (CSI 2010). As alternative disposal of the waste fuels may involve their incineration, or landfill, the lifecycle emissions of using the waste fuels in the kiln may be closer to zero (CSI 2010). Cement kilns are well developed for the disposal of waste fuels as mineral content in fuels is incorporated into the clinker, there is therefore no residual ash and heavy metal, as would arise if disposed of in an incinerator (CSI 2010). Although the UK's Committee of Medical Effects of Air Pollution has deemed the burning of waste derived fuels as safe for the local environment (Environment Agency 2005) there is often local opposition to the practice. The long term upper limit of fuel switching to waste fuels for developed countries is thought to be around 60% (CSI and ECRA 2009). The savings offered will be dependent on the fuels used and how the emissions are accounted for.

The use of carbon capture and storage technology has been proposed for the cement sector (Centre for Low Carbon Futures 2011, Element Energy 2010) due to the high emissions intensity of the manufacture and the high proportion of process emissions. Post-combustion and oxyfuel technologies may be suitable for use, 90-95% of carbon emissions can be captured through CCS (Centre for Low Carbon Futures 2011). The SEC of the process would increase significantly, with the addition of CCS, leading to high operational costs in addition to the substantial capital investment. There are large uncertainties regarding both cost and technical viability. CCS would be particularly suitable for large plants, and those located near existing power stations or potential carbon-dioxide storage sites, to minimise infrastructure costs.

There are a range of ‘alternative cements’ in development that offer potential for both lower energy demand and reduced process emissions (Centre for Low Carbon Futures 2011). These are very much in the development stage however, the penetration of such technologies into the well-established and proven OPC market is speculative. It is thought that these alternative cements would be unlikely to achieve significant market penetration in the near-term (before 2030).

The Cement subsector is classed as energy-intensive in the analysis of Chapter 4. The sector has values of all three criteria (energy-intensity, proportion of energy and water costs as a proportion of total costs and mean energy use per site) utilised in defining a subsector as energy-intensive well above the limits required. This indicates that Cement manufacturing should have strong drivers to energy efficiency improvements. The sector is also dominated by a small number of companies. There are five companies operating the fourteen kilns at twelve sites in the UK. Further the majority of cement production in the EU is owned by seven multi-nationals (Ponssard and Walker 2008), who also own significant facilities throughout the rest of the world (Croezen and Korteland 2010). There is therefore strong potential for technology sharing between sites under common ownership. The large size of the companies also implies that there should be sufficient resources to gain a good understanding of energy use and invest in research and development. At energy efficiency focussed events representatives of cement manufacturers were found to be in attendance. That the subsector employs energy managers is an indication of an importance that is placed on energy use. Capital should also be more easily garnered for new projects than it might be for a small company operating a single site. That energy costs typically represent 40% of operational costs for a cement manufacturer (European Commission 2010b) indicate that there is a strong driver for research into cutting energy use. Like the rest of the energy-intensive subsector, as discussed in Chapter 5 it seems Cement has made considerable improvements in energy use since the 1970s and further improvements appear difficult without more radical changes. However due to the strong drivers to improving energy use and reducing emissions these radical options are receiving attention.

7.3 DISCUSSION

The two subsectors of industry examined here are a good example of the diversity throughout industry. They both account for substantial amounts of emissions in the industrial sector, but are very different in the way energy is used. The Food and drink subsector, being diverse in regards to energy use, required a top-down approach to improvement potential. In contrast the Cement subsector is very homogenous in its process routes and energy use, allowing a more detailed, bottom-up approach. The top-down approach to the Food and drink subsector, focussing on low temperature heat and steam systems, allowed good coverage of energy use. This coverage would not have been possible with a bottom-up approach. The top-down approach meant that the findings are not as detailed as could be given with a bottom-up approach however. The bottom-up approach in the Cement subsector allowed a reasonable coverage of energy use, due to the domination of the kiln in regards to energy use and emissions. The application of technologies were assessed down to the level of different kiln types. The ability to define baseline energy use in the Cement subsector at a detailed level, which was not possible in the Food and drink subsector, was more felt to be more important in assessing improvement potential in this bottom-up manner than information on technologies.

In terms of relative improvement potential the Food and drink sector and Cement subsector show broadly similar results from the analysis conducted in the current chapter. In terms of final energy demand of the subsector the individual options examined for low temperature heat in the Food and drink subsector could save up to 21% of the baseline demand. Within the Cement subsector up to 17% of final energy demand could be saved through conversion to BAT. In terms of GHGs the Food and drink subsector could save up to 8% of current emissions, through any of the available measures. The Cement subsector could save up to 14% of its current emissions, through clinker substitution increases. The measures examined in the Cement subsector could potentially all be employed in tandem (although the effectiveness of each is likely lessened by the use of the other measures). Conversely the technologies examined for the Food and drink sector cannot be applied to meet the same demand. The Food and drink sector will likely have significant potential for savings not examined here, in motor systems, refrigeration and other technologies. Improvement in the Cement subsector away from the kiln is limited to small improvements in the motor systems used in mixing and grinding operations.

The character of the subsectors is illustrated in the historical improvements in energy efficiency and the future potential. The Food and drink subsector has shown gradual improvement in energy intensity since the 1970s and potential for continuing this improvement at a similar rate is thought to exist. In comparison to Cement subsector has shown large improvements in its energy use, both through structural changes and efficiency improvement through the 1970s to 1990s, but further potential improvements of this magnitude are thought to be limited with current technology. These two subsectors therefore encapsulate the differences found between the energy-intensive and non-energy-intensive subsectors of industry, in the decomposition analysis of

Chapter 5. In the longer-term the options for further improvement in the Cement subsector will likely be through more radical technologies. The structure of the Cement subsector means the RD&D support required to realise these more radical opportunities is available. Although the Food and drink subsector does not benefit from the same resources, it will benefit more through the development of cross-cutting opportunities.

7.4 SUMMARY

The UK Food and drink and Cement subsectors have been examined in terms of their current energy use and efficiency improvement potential. Due to the differences between the subsectors the Food and drink subsector was treated in a top-down manner, whilst when analysing the Cement subsector a more bottom-up approach was taken. These two subsectors well illustrate the diversity within the industrial sector and how the longer-term potentials for reducing emissions are influenced by the character of the subsectors. This diversity was found to be prevalent both in the data availability and attitude towards energy issues of the subsectors. At the subsector level it was found to be necessary to obtain energy use information from sources other than the publically available datasets that cover the whole industrial sector.

The Food and drink sector energy demand is dominated by low temperature heat. Efficiency improvements assessed therefore concentrated on this area, improvements to existing steam systems, supplying heat with CHP systems and with heat pumps, were all examined as possible options. The emissions savings possible through each approach were similar. In the short-term improvements to existing systems would be most likely to be adopted. With the availability of capital, sufficient drivers to reducing energy use, and, in the case of heat pumps, the maturing of technology, alternative methods of heat supply would be expected to increase. A decomposition analysis revealed that the Food and drink sector has been making continual improvements, at a constant rate, in energy intensity since the 1970s. Due to the non-energy-intensive nature of the majority of the subsector, this would be expected to continue.

The Cement subsector’s energy demand and emissions are dominated by the kiln. This is therefore the focus for assessment in the current chapter. A decomposition analysis suggested that further improvements in the current process are likely to be limited. Whilst some potential for improving the efficiency of existing kilns was identified, these are unlikely to be fully realised by the subsector. A small opportunity for generating electrical power from excess heat was also found. The greatest opportunity to limit energy demand and emissions was found to be the reduction of kiln output by substituting alternative materials in place of the clinker output from the kiln. In the longer term to make significant reductions the sector will likely rely on CCS and/ or alternative cement materials, fuel switching may also play a role.

CHAPTER 8

DISCUSSION

The broad aim of this thesis, as defined in Chapter 1, was to assess the current state of energy use in the industrial sector of the UK, and the prospects for reducing this energy use. In defining the scope of the work, and subsequently the objectives of the work, in Chapter 1 it was necessary to give the work focus in a manner that involved a compromise between maintaining a breadth to the work that gave it interest and impact, and also not becoming too broad to prevent significant findings being made. Here in discussing the results of the work undertaken the scope is broadened. Generalisations are drawn from the work and methodologies discussed, the influence of areas outside the scope of the thesis on the findings are also examined. The results of the work in individual chapters have been discussed, where applicable, in the relevant chapter and so the discussion here only covers these broader issues.

8.1 GENERALISATION OF RESULTS

In drawing out generalisations from the work undertaken in the thesis, the focus has been on findings that can be applied throughout industry, or to areas that represent significant proportions of energy use. The use of top-down and bottom-up studies in terms of how, and where, they can effectively be applied in the industrial sector is an important concept in this regard. The differences seen in energy-intensive and non-energy-intensive subsectors, as defined in Chapter 4, in terms of how studies are utilised, and how the subsectors differ their future improvement potential is also discussed.

8.1.1 Top-down and bottom-up studies: suitability and findings

The primary challenge to fulfilling the aim of the thesis was identified in Chapter 1 as the variability in energy use throughout the sector. Coupled with the limitation imposed by the availability of good quality data, especially in defining the baseline energy use (as discussed in Chapter 2) this variability led to the approach taken. The current work conducted a number of separate, but interlinked, studies of improvement potential using different levels of disaggregation. One of the important concepts in the work, which was introduced in Chapter 1, was the use of both top-down and bottom-up studies at different disaggregation levels.

Top-down studies rely on those datasets publically available (which were discussed in Chapter 2) or constructed using available data and assumptions (as was performed in Chapter 3). Such datasets have been used in studies that cover a wide proportion of the industrial sector (see for example Chapter 3 and Chapter 5). The reliance on such sources of data is not without concerns regarding the manner in which data is available and its accuracy, as discussed in Chapter 2. The conclusions that can be drawn from these studies therefore often have a high level of uncertainty. Whilst bottom-up studies allow a more accurate assessment of energy use and improvement potential, they require a well-defined subsector, or process, as the focus. The limitation of such a study is then whether it can cover a meaningful proportion of industry. The Cement subsector is an example where such a bottom-up methodology can be applied (see Chapter 7), due to the characteristics of the subsector.

During the work a combination of both top-down and bottom-up approaches was used when undertaking the assessment of opportunities for waste heat recovery in Chapter 6. Here a database was established by utilising site-level emissions data alongside assumptions regarding energy use, based on the classification of the site (see Chapter 3 and Chapter 6 for more detailed discussion of the methodology). As the sites involved were significant users of energy the assumptions used in constructing the database were, in many cases, based on a bottom-up approach. There were some subsectors that necessitated a general approach, more akin to a top-down study. This database and the analysis undertaken in both Chapter 3 and Chapter 6 therefore had some of the advantages, but also some of the limitations, of both top-down and bottom-up approaches. It did not cover the whole of the industrial sector, but was felt to be more accurate in key areas than other datasets. The database also supplied well-defined heat demand data at the site level, which was not available in alternative top-down datasets, thus allowing the analysis of Chapter 3 and Chapter 6 to be undertaken.

In principal, all subsectors of industry could be represented by bottom-up studies if a high enough level of disaggregation were employed. This would avoid many of the inaccuracies faced when relying on broad datasets, and assumptions regarding improvement potential. In practice however such an approach is not reasonable if the aim is to cover significant amounts of energy demand. Such a bottom-up approach was considered when initially approaching the analysis of the Food and drink subsector, presented in Chapter 7. The feasibility of performing bottom-up studies on the largest energy using subsectors within the Food and drink subsector was investigated. As discussed in the relevant chapter, this was not practical due (primarily) to data constraints, but also as the subsectors and processes that would be suitable for bottom-up studies did not account for large proportions of total subsector energy use. This lack of data is felt even at the site-level by companies. In the course of the present research contact with companies within the Food and drink subsector in the UK revealed poor data availability, regarding current energy use, and lack of staff time to address this issue. The companies involved appeared motivated in improving their energy use. This therefore illustrates the importance of the barriers created by lack of information and lack of staff time within the subsector (drivers and barriers are discussed in Chapter 4).

8.1.2 Improvement potential: broad findings and realising the potential

Based on the discussion above it can be argued that, as a general approach, the energy-intensive subsectors of industry (as defined in Chapter 4) are well-suited to bottom-up studies, whereas the non-energy-intensive subsectors are better suited to top-down studies. This is due to data availability, but also the characteristics of the subsectors themselves, and the options for improvement in energy use. Within the energy-intensive subsector, energy use is often dominated by a unique, high temperature process. Improvements to such a process would not easily be evaluated via a top-down assessment. Conversely, in the non-energy-intensive subsectors, the unique processes tend to involve lower temperatures (see Chapter 4), and therefore show better prospects for cross-cutting technologies. Such processes also tend to be less significant in terms of the overall energy demand of the subsector. This generalisation is discussed further in the current section with exceptions identified.

The top-down approach to improvement potential undertaken in Chapter 3 examined opportunities available in motor systems, steam systems and in the increased use of CHP technology. Similar savings in terms of primary energy and GHG emissions were offered through each of these options, although there is some conflict between the application of both steam system improvements and CHP. In terms of where within industry these options are applicable, motor systems were found in Chapter 4 to be responsible for relatively greater demand in the energy-intensive subsector. However, it is thought, following the analysis in Chapter 5, that the improvement opportunities offered by motor systems may be relatively greater in the non-energy-intensive subsector. This is because the energy-intensive subsector often has less residual potential for easily implementable improvements in energy use. The steam system improvements are likely to be greatest in the non-energy-intensive subsector for similar reasons, and as the majority of low temperature heat demand is in the non-energy-intensive subsector. CHP opportunities were identified in both the energy-intensive subsector (Chemicals and Pulp and paper) and non-energy-intensive subsectors. Although lower temperature demand suitable for supply through CHP is relatively greatest in the non-energy-intensive subsector a minimum size of site is also required for CHP to be viable, which means many sites within the non-energy-intensive subsector may not be suitable for the technology. CHP is immediately available and cost effective in many cases, offering primary energy and GHG emissions savings in comparison to on-site heat generation and centralised electricity generation (see Chapter 3 and Chapter 7). Lack of capital was identified as a strong barrier to the realisation of this potential. The ease and expense with which CHP can connect to the grid could be improved to facilitate a higher rate of CHP uptake, this is an area where regulation may need to change (Kelly and Pollitt 2010). As CHP is currently fired by fossil fuels in the majority of cases (DECC 2012d) it still leads to carbon emissions. It is therefore seen as a transition technology by the UK government (DECC 2012h) that can offer improvements on the current situation, before itself being replaced. Whether all CHP opportunities should be pursued currently is a question that requires a holistic approach with consideration given, not just to immediate benefits, but also the impact on the future energy system caused by technological lock-in. The current government view is that, after 2030, fossil-fuelled CHP will be discouraged. Fuel switching at CHP installations to biomass, biogas and waste combustion after this date is expected. In addition other lower temperature heating options such as the use of heat pumps using electricity generated by renewables may be adopted (DECC 2012h). However, there is considerable uncertainty regarding system level opportunities for the decarbonisation of electricity generation and the availability of biomass. These uncertainties and the ability of existing installations to fuel switch without the purchase of entirely new plant are considerations for the longer-term strategy regarding industrial CHP.

The analysis of the Food and drink subsector, in terms of assessing improvement potential in low temperature heating processes, could be extended to the majority of non-energy-intensive subsectors (as defined in Chapter 4). The Food and drink subsector itself comprises a significant proportion of energy demand within the non-energy-intensive subsector, approximately 25% on a final energy basis. A significant demand for low temperature heat is also common throughout the non-energy-intensive subsector (see Chapter 4). This discussion draws on Chapter 7, Chapter 6 and Chapter 3. Low temperature heat is a large user of energy within industry and has a number of potential technologies that could improve both its supply and use. As discussed in Chapter 1, Chapter 3 and Chapter 6 higher efficiency is an important initial step in improving energy use, even when an alternative supply exists. Efficiency measures are immediately available in many cases (both from a technical and economic perspective) and make supplying the demand in an effective manner an easier proposition. Continued incremental improvements in efficiency are expected to continue in the short-term to medium-term within the non-energy-intensive subsector. The opportunities for steam systems identified in Chapter 3 are an example of these. Waste heat recovery can also be used in improving the efficiency of processes. In Chapter 6 approximately 60% of energy demand from the Food and drink subsector was included in an analysis of waste heat recovery opportunities. There was potential identified within the subsector for on-site heat recovery, absorption chilling and heat transport for use offsite. When a combination of waste heat recovery options was assessed, on-site heat recovery dominated, and was capable of saving approximately 1.5-3PJ/yr of final energy. This was smaller than savings offered through steam system improvements, CHP and heat pumps as assessed in Chapter 7, but (because of the partial coverage of the subsector and its conservative nature) this is likely an underestimate. Another study by Reay (2008) estimated a potential to recover 8PJ/yr of waste heat in the subsector.

Heat pumps offer improvement potential in supplying low temperature heat, and are therefore best suited to the non-energy-intensive subsector. They are a relatively new technology in the industrial sector, and so would be expected to develop, in terms of cost reductions, and the temperatures that could be supplied. In Chapter 7, within the Food and drink subsector, heat pumps were found to offer lower potential than CHP in saving primary energy and emissions under current conditions. They have the potential to increase emissions savings with decarbonised electricity, and are suitable for application at the smaller-scale than typical industrial CHP plants. An analysis comparing the use of CHP to that of conventional power generation and heat pumps shows that from a thermodynamic sense CHP is the superior technology from a primary energy and emissions sense. This is likely to remain the case, especially if CCS technology could be used with CHP plants. The increased use of CHP therefore provides an alternative option to the electrification of heat (Lowe 2011). There are many uncertainties surrounding the contribution that CCS will make to both electricity generation and industrial plants (Element Energy 2010, Hammond et al. 2011, IEA and UNIDO 2011), but its use with a CHP plant would likely require a large-scale plant. If

CHP plants, fitted with CCS, were to be utilised within the non-energy-intensive subsectors of industry, it is likely to require the use of a large plant to supply a number of local industrial sites and/or domestic and commercial buildings. The existence of a heat network would make the sharing of such a large heat resource possible. Such a network would also facilitate the use of waste heat between industrial sites as discussed in Chapter 6. The use of such networks would be challenging from a technical, economic and social perspective, but does hold considerable potential, both within industry, and throughout the domestic and commercial sectors (DECC 2012h).

As discussed in Chapter 5 the energy-intensive subsector has historically made greater relative improvements in energy efficiency than the rest of industry and further incremental improvements in efficiency may be limited, this means that future opportunities tend to involve more radical departures from current technology. This was found to be the case for the Cement subsector, as examined in Chapter 7. There was also considerable potential identified in Chapter 6 through applying various waste heat technologies to the energy-intensive subsector. These will rely on the development of low temperature heat exchangers, heat-to-power technology, and heat networks to be fully realised however. Greater longer-term improvements in the energy-intensive subsector will also likely depend on the development of CCS technology, the availability of biomass (including biogas) and decarbonised electricity (as are longer-term improvements related to low temperature heat, as discussed above), as well as the potential to alter processes to use these energy sources. Radical changes in the process or product itself may be required to complement these approaches. Research and Development is likely needed to realise these longer-term options, although the UK has shown little public investment in this area, in recent years (see Chapter 4). Studies such as the Technology Innovation Needs Assessment (Low Carbon Innovation Coordination Group 2012) identify where such research could perhaps be targeted most effectively. Many industries seem hopeful that CCS can effectively be developed, so that operations can continue with minimal disruption in a carbon constrained future. Even in the best case scenarios regarding CCS technology it will involve significant increases in cost and energy demand however.

The potential to realise any of the improvements discussed above is dependent on the drivers and barriers to the technologies, as well as the effect of policy in influencing these (this is discussed further in Chapter 4). How these drivers and barriers impact differentially within the energy-intensive and non-energy-intensive subsectors is important. The effective coverage of the non-energy-intensive subsector was an area identified for future policy improvement in Chapter 4. Despite some concerns regarding the effectiveness of current government policy relating to energy efficiency, it is hoped it can be effective in the difficult area of encouraging the take-up of efficiency measures without harming economic development. A likely driver to continued efficiency improvements, which could both be influenced by policy and wider issues, is an increase in energy prices. Whilst there is considerable uncertainty regarding future energy prices, they are generally expected to increase over time (DECC 2012l). As discussed in Chapter 5 the effect of energy price increases on efficiency is not straightforward. Although such price increases are often thought of as a driver for efficiency, and there is some evidence in this regard, they can also stifle growth, innovation, and investment which can in turn have a negative effect on energy efficiency. This negative effect of price increases on efficiency is often argued by energy-intensive companies (Centre for Low Carbon Futures 2011).

8.2 EXTENSION OF RESULTS AND LIMITATIONS

The thesis has examined energy use and improvement potential within UK industry. Industry is only one subsector of the wider economy, whilst energy demand and its emissions are one component of sustainability, and the UK is just one nation in the world. Each of these factors is a key limitation on the current work. In focussing on one area the optimal solutions from a wider perspective may be overlooked, the focus of this section is therefore how the findings of this research can be extended beyond the scope adopted, and also what the limitations are of the current work.

8.2.1 Industry within the wider economy

Industry can influence energy use and emissions both upstream and downstream of its operations. Similarly industrial energy use and emissions can themselves be influenced by actions outside the sector, which is discussed in section 8.2.2 below. These considerations have not been explicitly included in the current work. The Food and drink subsector is used here as an example of the effect of such considerations, building on the evaluation of the energy use and emissions that the subsector is directly responsible for in Chapter 7. In terms of the production chain of Food and drink in the UK, the manufacturing operations, as included in the analysis of Chapter 7, comprise only around 10% of the total GHG emissions. Fig. 8-1 shows how emissions throughout the production chain are split. Agriculture dominates emissions with non-energy-related methane from livestock and nitrous oxide from fertilisers being most significant. The emissions from transport, retail and domestic parts of the production chain also have at least as significant an effect on overall emissions as the manufacturing operations. Waste can also cause considerable methane emissions from landfill sites (FDF 2008) and isn’t included in the breakdown shown in Fig. 8-1.

The outcome of the breakdown in emissions discussed above is that the manufacturing sector can only influence a proportion of a product’s lifecycle emissions when controlling its direct emissions. The manufacturing sector could, in some cases, have a more pronounced positive effect by influencing other areas of the lifecycle. In the example of a food manufacturer, by sourcing ingredients in a manner to minimise emissions, both in their production and transport, indirect emissions could be reduced. One method to assess the impact of a product and potential improvements over the whole production chain would be Environmental Lifecycle Assessment (LCA). However such an approach is time intensive and only suitable when a single, well-defined, product is of interest. A method to account for the flows of products and their energy use through the economy is input-output (I-O) analysis. The analysis was originally developed for economics purposes, but can be adapted for use in energy analysis (Casler and Wilbur 1984). I-O analysis therefore offers a greater coverage of products than LCA, but does not offer the analysis of environmental effects other than energy use and emissions, and the products analysed are limited by the disaggregation of I-O tables.

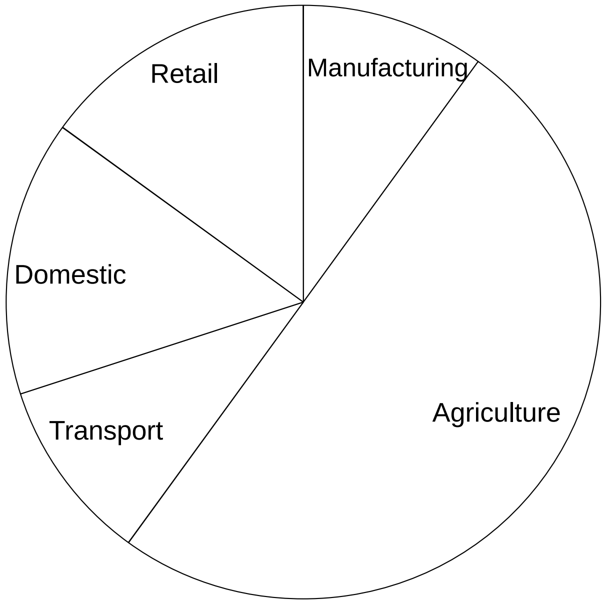

Fig. 8-1: Approximate split in GHG emissions from each stage of the food production process, source FDF (2008).

8.2.2 Production output and efficiency

The influence that output and the structure of industry have on industrial energy demand is obvious on one level, manufacturing more product, or more energy-intensive products, will necessarily involve the use of more energy. Output can also influence energy demand more subtly however, as discussed in Chapter 5. Energy efficiency improvements can be driven by an increasing output, through investment in new plant and by running existing installations at optimal capacity. The recent recession experienced in the UK and the partial recovery that has happened up to the current time has had a large influence on industrial energy demand and the structure of certain (mainly energy-intensive) subsectors, see Chapter 3 and Chapter 7. How the economy recovers from the current situation (the post-2008 recession) could have a considerable influence on long-term energy use in the UK.

Consumer preferences have potential to alter the level and structure of output, and so the energy demanded from industry, and linked supply chains. Consumer preferences for products with a low ‘carbon footprint’ could drive manufacturers to improve energy use in all stages of a production chain in trying to capture this market. This could involve a change in the product output. To use the example of food production a preference for vegetarian, locally produced, fresh food could serve to minimise energy use and emissions (although there are other factors that could influence the overall energy intensity of food production, such as the reliance on heated greenhouses to produce foodstuffs locally, the yield of crops and food wastage). Within the food industry it has been found that whilst consumers show a preference for ‘carbon labelling’, there is a high level of confusion regarding such labelling (Gadema and Oglethorpe 2011). Therefore there has not been a high demand for ‘low carbon’ food products. The food industry, in recent time periods, has experienced a shift towards increased processing during manufacturing (as opposed to domestically), and a higher standard of hygiene. These effects have acted to increase energy use in the manufacturing subsector of Food production (Ramirez 2006).

Another manner in which the output of manufacturing can be influenced and subsequently the energy demand reduced is through higher levels of material recycling and reuse. As an example manufacturing steel from recycled stock is significantly less energy-intensive than manufacturing primary steel from ore, however there is also potential to directly reuse steel products, such as structural beams, when buildings reach the end of their life (Allwood and Cullen 2011). This would require a considerable change in the supply chain of some products, but it has a large potential benefit in terms of reducing energy demand. The longer term curtailing of demand for products, and constant economic growth, could obviously have a large influence on industrial energy demand, but is a contentious issue and beyond the bounds of the present work.

When an efficiency measure is applied to industry the subsequent energy savings are not always as great as predicted. This can be due to the installed technology being utilised in a suboptimal manner, for example maintenance procedures may be inadequate. The full savings may also not be realised due to the rebound effect, which was described in Chapter 4. When energy efficiency is improved there may be effects that increase the output of energy demanding services. This can be within the same site or subsector as the application of the efficiency measure, or can be an indirect effect on other areas of the economy. The rebound effect has not been considered in detail in the current study, but when examining the effect of efficiency holistically is an important consideration. However, it is not one that can be easily measured [see for example Greening et al. (2000), Nadel (2012), Saunders (2000) and Sorrell (2009) amongst others].

8.2.3 The UK industrial sector as part of a global system

The UK has seen reductions in energy demand in the manufacturing sector since the 1970s. As shown in Chapter 5 this is through an improvement in energy intensity (with some contribution from a restructuring to higher value added products), coupled with limited increases in output. This reduction in industrial energy demand is not the case globally, especially within developing economies. Current projections suggest that, up to 2030, almost all (93%) of global energy demand growth is likely to be in non-OECD countries (BP 2013). Industry is predicted to lead the growth in final energy demand globally, accounting for 57% of this growth by 2030 (BP 2013). Much of this increase in growth is expected within energy-intensive subsectors. As shown in Chapter 7 a country’s cement production is linked to economic growth. Although energy use in the UK cement subsector has declined since the 1970s, and has been fairly steady in the EU (European Commission 2010b), it is growing substantially in the developing world. Worldwide production has increased enormously, reaching 4.4 times the production of 1970 in 2007 (IEA 2009). China now dominates world production, manufacturing 47% of the world’s cement, with India being the next largest producer, accounting for 6% of world production (IEA 2009).

The growth in industrial energy use in the developing world is partly for its own development, especially for products such as cement that are not often internationally traded (see Chapter 7). The growth in energy demand can also be for products that are manufactured in the developing world, where production costs are less, but ultimately are consumed in the UK. It can therefore appear that energy demand of UK manufacturing is declining, whilst the energy demand related to the consumption of manufacturing products is by contrast increasing. This is linked to the notion of carbon leakage as discussed in Chapter 4 and Chapter 5. An international input-output analysis can be used to indicate the consumption based energy demand and emissions of a country across international borders (Minx et al. 2009). Another method of assessment is the calculation of a nation's 'carbon footprint' (or 'carbon weight'), with consideration given to the imports and exports of the nation (Cranston and Hammond 2012).

Although much of the analysis here has focussed on the UK there is some application of the current work to the industrial sectors of other countries. Such technology transfer can contribute to developing nations growing in a more sustainable manner. There is some evidence of this, with an example presented from the cement subsector. High levels of growth in developing countries can lead to investment in new plant that tends to be of modern technology (often developed in other nations) and of good efficiency. The average efficiency of a cement kiln in China is better than that of the USA and Canada (IEA 2009). This technology transfer can also apply to improvements in UK industry being built on the activities of other nations. Much of the technologies discussed in this work have been successfully used or developed in other countries before the UK. For example, heat networks, (as discussed in Chapter 6) are much more extensive in some European countries, particularly Denmark, Sweden and Finland, than in the UK (DECC 2012h).

Comparing the energy efficiency performance of countries is best done when comparing well-defined processes or subsectors to allow for differences in structure. However, comparisons at a more top-down level can still provide useful insights. One such comparison is that of Farley et al. (2012) which examined and rated the energy efficiency of different nations' industrial sectors as part of an economy wide rating. The industrial sectors are rated in terms of energy intensity, CHP use, R&D spend, voluntary energy performance agreements, and whether it is mandatory for companies to have energy managers and conduct energy audits. The UK rates highest of the twelve economies assessed in terms of industrial energy efficiency, closely followed by Italy, France, Japan and Germany (the UK also comes top in the overall rating for the economy, including measures of energy efficiency in building, transport and at the national level). There are some limitations with the study: the energy intensity measurement does not take account of industrial structure and so favours economies that manufacture higher value added products. The CHP assessment gives a top-rating to a level of 25% or more of electricity demand being through CHP generation. The UK achieved a top-rating here, but (as discussed in Chapter 3 and Chapter 7) there is still thought to be considerable potential for increasing the use of CHP in UK industry. The UK scores poorly on R&D spend, as would be expected given the findings in Chapter 4. Voluntary agreements are an area where the UK scores highly, due to the CCAs (which are discussed in Chapter

4). Having no mandate for energy managers or energy audits lost the UK points. Although the rating should be taken with a 'pinch of salt', especially regarding energy intensity (the highest rated factor in the overall score) it does indicate areas where attention may lead to efficiency improvements. Focussing on the areas the UK scored poorly, increasing R&D spend towards energy efficiency in manufacturing could help stimulate improvements (as discussed in Chapter 4) and the existence of an energy manager and mandatory audits could help overcome the barriers of lack of information, as well as lack of staff training and time. The experience of other countries that perform better in these measures could provide lessons for the UK.

The existence of large international companies that operate not just in the UK, but worldwide has implications for energy efficiency. Technology developed in one nation can most easily be transferred to another if it does so intra-company. A large multi-national is also more likely to fund R&D that leads to reductions in energy demand. Lack of capital for efficiency projects is less likely to be a significant barrier to energy efficiency improvements in such a company. Conversely, however, a site in the UK that is part of a multinational can also be competing against other sites within a company, including internationally, for rationed capital. The chances of securing such capital are harmed if local conditions are not as encouraging to such an investment as those in another nation (Centre for Low Carbon Futures 2011).

The main limitation of the present work in respect to scale discussed here, has been in regard to the fact that the UK is just one nation in a global economy. However, the actual realisation of efficiency and improvement potential often requires action at the local level. An example of such a situation is a heat network. Given the lack of a nationally managed heat market, local authorities can be pivotal in helping to develop heat networks (DECC 2012h) They can assist in both the construction and operation of the networks and the contracts between users. An example where local industries are investigating the potential at a regional level for a network to share industrial heat resources is the North East of England Process Industry Cluster.

8.2.4 Beyond technical aspects

This research has focussed on energy use of industry and the related GHG emissions; the mechanisms to improve these have been primarily technologically based. There are other components to the notion of sustainability however (Parkin 2000). In particular reference to the impact of manufacturing activities on the use of resources, such as minerals and water, are clearly important (Scott et al. 2009). Additionally the effect of industrial activities on local communities, both economically and environmentally, has not been considered in detail here. As discussed in Chapter 4 and in other studies (Reason et al. 2009, Von Weizacker et al. 1997) there is a human aspect to consider, alongside technological issues, in realising potential energy saving. There are concerns, for example, about whether improvements in efficiency and other aspects of energy can be enough to mitigate climate change without corresponding lifestyle changes (Adua 2010). These tie into the discussion of output and efficiency above, but would require changes in consumer attitudes that cannot be assessed through technological measures alone.

8.3 SUMMARY

This thesis reports the outcome of a number of interlinked, but separate, studies from a top-down and bottom-up perspective. Bottom-up studies are generally limited in their effective application to large, energy-intensive subsectors where unique energy using processes comprise a substantial proportion of energy demand. Significant improvements in emissions in these areas are likely to rely on radical process changes alongside the development of CCS and alternative fuels. The non-energy-intensive subsector is better suited to top-down studies, and a cross-cutting approach, in attempting to cover substantial areas of industry. Relatively greater incremental efficiency improvements are thought to exist in the non-energy-intensive subsector. Areas of technology development, or application, that could improve efficiency throughout the sector include motor systems and steam systems improvements, as well as the increased use of CHP, heat pumps, heat networks and waste heat recovery technologies.

UK industry is one component of the wider global economy. Activities outside the industrial sector can influence its energy use and similarly it can impact on energy use in other areas of the economy. Being part of a global system, lessons can be learnt from and shared with other nations, with much of future industrial growth expected to be outside developed countries. Efficiency is one important strategy to improve energy use and the technical assessment undertaken as part of this research is one way of evaluating its impact. A 'toolbox' of assessment techniques and approaches can consider other strategies for saving energy and emissions. Efficiency and technological appraisals are synergistic with many of these alternative approaches.

CHAPTER 9

CONCLUSIONS

This chapter concludes the thesis with a rationale for the work undertaken, explains how the objectives of the thesis have been met, and the conclusions drawn in this regard. It discusses the contribution to knowledge made by the work and highlights areas for future research that have arisen.

9.1 RATIONALE

The industrial sector is responsible for significant energy use and GHG emissions within the UK economy. Reducing these GHG emissions, much of which are energy-related, is important in achieving carbon reduction targets. Energy demand reduction is an effective way to mitigate emissions, and can assist in ensuring the energy security of the UK, as well as in facilitating a shift to more renewable forms of energy supply. Energy efficiency improvements are an effective method of reducing demand and can often be undertaken both immediately and economically. The broad aim of the work was to assess the current energy use of the industrial sector and its improvement potential, a number of interlinked studies and approaches have contributed to this aim, as detailed below.

9.2 MEETING THE OBJECTIVES OF THE THESIS

The conclusions of the work are related to the objectives of the thesis outlined in Chapter 1.

1. **To assess the different methods of defining and measuring energy efficiency.**

   These conclusions are based on the work undertaken in Chapter 2. There are two important aspects to defining and measuring energy efficiency: the measure of energy input, and the measure of useful output. In defining energy input and output the system boundary can have a significant impact and should be chosen carefully. This should consider the aims of the study, but also the limits imposed by data availability. In assessing industrial energy efficiency in the context of the current work direct (or process) energy use, rather than the gross energy requirement (GER) was of principle interest. The primary energy use and GHG emission implications of the direct energy use were also considered, where appropriate. The most suitable measure of useful output is determined by the type of study and data availability. For certain processes, output can be measured thermodynamically, as discussed under objective 2 below. This is not always suitable however. Dependent on the area under investigation, it can be difficult to define output in thermodynamic terms. Measuring output in physical terms is often appropriate at the level of a process, site, or well-defined subsector. Economic output measures generally have to be utilised when outputs are of a mixed physical nature. Techniques are available to utilise physical outputs of a mixed nature, but the large data requirements of such methods often limit their use. Physical output measures are preferred where available however, as economic measures are subject to the influence not only of real physical output, but also imperfect price indices. The economic output measure found to correspond best to physical output was value of production. The specific energy consumption (SEC) (the energy demand per unit of physical output) is the preferred efficiency indicator. If this is not appropriate, due to mixed physical units or data constraints, then energy intensity (energy demand per unit of economic output) can be utilised. All efficiency indicators rely on comparison (whether this be with another process, subsector, nation or time period) or can be meaningless.

2. **To review thermodynamic, engineering and economic techniques and their application to industrial energy use.**

A review of these techniques with reference to the current work was undertaken in Chapter 2, and the techniques were used to some extent throughout the thesis. The techniques of thermodynamic, engineering and economic assessments each have their place in an analysis of improvement potential, and in fully considering the issue each should be applied in turn. Thermodynamic analysis is most simply employed at the process level, by defining energy flows into and out of a process. Other thermodynamic measures, such as exergy, can similarly be used. These techniques can also be applied at the level of a site, or subsector. At a higher level, more assumptions are required and not all energy flows can be accounted for, making the findings more indicative. Sankey diagrams (and Grassman diagrams) were useful in visualising thermodynamic flows at various points in the work. The use of exergy analysis has some place in the current work. It can offer insights into where efforts should be focussed in efficiency improvement, especially at the process level. In addition, it was useful when examining the conversion of waste heat resources to electrical power. At the broader level, when applied in a more top-down manner, exergy analysis can be limited in its conclusions. Similar insights may be gained from applying energy analysis together with a basic understanding of the second law of thermodynamics. Exergy analysis should always be used alongside energy analysis to offer additional insights, not in preference to energy analysis, or in isolation.

Whilst thermodynamic analysis is an engineering technique the two are separated here so an 'engineering approach' allows a more pragmatic assessment of improvement potential than thermodynamic analysis. This approach takes account of technical limitations alongside thermodynamic constraints. Engineering techniques were used extensively throughout this work, both in top-down and bottom-up assessments of technologies.

A number of economic criteria can be evaluated when assessing a project, for example net present value (NPV), payback time, and rate of return on investment may all be considered. Such criteria have been utilised in the current work in assessing the economic potential of efficiency measures. Whilst some of the analysis methods employed in this work (such as decomposition analysis, and the drivers and barriers assessments) could be considered to be within the domain of economic techniques, they are discussed separately below.

3. **To examine the drivers and barriers to improving energy efficiency and the way in which current policy influences these. Furthermore to assess the way these drivers and barriers vary throughout the sector.**

   The work related to this objective was conducted within Chapter 4. The focus of the assessment of drivers and barriers was not on thermodynamic or technical constraints, but rather what determines if an efficiency measure is considered economic, and further, what influences the adoption of the measure. This helps to determine why seemingly viable and profitable technology options are not realised. At a sector level, the drivers to energy efficiency improvements were identified as being principally cost driven, although the commitment of an individual or company to improving energy use could also be important. Cost savings included those directly realised through energy savings, and those obtained via opportunities for reducing carbon, as well as hidden benefits (such as increased productivity, and improved reputation through a commitment to reducing energy use).

   Barriers were found to be more numerous and diverse than drivers. They are often dependent on the characteristics of the improvement measure and subsector. The most prevalent barriers were found to be lack of information, a focus on production, and hidden costs associated with efficiency measures. There was some discrepancy regarding the impact of lack of capital as a barrier to energy efficiency. It was felt that in some companies, and for some projects, this could be a significant barrier.

   The variation of barriers throughout the industrial sector is complicated, in contrast to drivers, which could more easily be defined through a number of quantitative criteria. Such criteria were used to separate the sector into an energy-intensive subsector, with stronger drivers to energy efficiency, and a non-energy-intensive subsector, with weaker drivers. The criteria used for this split were the energy intensity, the percentage of costs represented by energy, and energy use per site. The energy-intensive subsector was found to be responsible for 62% of energy demand, or 28% by value of production. In terms of energy use, heating processes dominate throughout industry with the vast majority of high temperature demand occurring within the energy-intensive subsector.

   Current policy affecting energy efficiency within the industrial sector has faced a difficult balancing act in terms of driving efficiency improvements, whilst not harming economic growth. This has led to current targets imposed by policy (such as the EU ETS and CCAs) often being easily met. However, the awareness engendered by the existence of such policies, and the required negotiation processes in setting targets, was found to have a significant effect. Future policy could benefit from simplification, with clear long-term targets; support of RD&D; a holistic approach to energy (including recognition of efforts to reduce energy use in other parts of the product's lifecycle); and an understanding and allowance for carbon leakage. In terms of the latter, an international agreement would be desirable, but is recognised as difficult. It was also found that the non-energy-intensive subsector of manufacturing was often overlooked by policy.

4. **To determine the best datasets for assessing the manufacturing sector in a top-down manner and to use such a dataset to examine broad options for decreasing energy use and carbon emissions.**

   Statistical datasets available for UK industry were discussed in Chapter 2. It was found that these were limited in their application to energy analysis, being either too aggregated to allow an assessment of improvement potential, or (at a more disaggregated level) having limitations regarding the accuracy. These limitations are often caused by the SIC system of classification used in such datasets. This system is based on product output characteristics, rather than the energy using processes. A database constructed from site level emissions data reported under the EU ETS was built to overcome these limitations. This constructed database offered a level of disaggregation more consistent with the needs of energy analysis, with site level information and a well-defined heating demand split into temperature bands. The database was also shown to be more accurate than alternatives in some instances. The limitations of this database were its partial coverage of industry (60% of industry, or 90% of energy-intensive industry in terms of energy demand), and its restriction to a particular time period (2000-2003).

   A thermodynamic analysis of the industrial sector was undertaken using this constructed database. The energy and exergy efficiency from a final energy perspective were estimated at 51% and 34% respectively. Broad assumptions regarding the efficiency of different processes were required by the analysis. The difference in exergy and energy flows were only due to the temperature requirements of energy demands, which are defined by the processes, and cannot usually be altered.

   Improvement to motor systems, steam systems, and the increased use of CHP systems were assessed in regards to the potential offered at the top-down level. The savings through each option were similar in terms of primary energy and emissions savings, each technology offering saving of approximately 5-7MtCO_{2e}/yr. Whilst each of these improvement potentials is available in the near-term, the increased use of CHP would involve more capital investment and so uptake of the opportunities would be expected to be slower. In the longer-term, if supplies of decarbonised electricity and or biomass are made available, (there are uncertainties here) a change may be expected towards electrically-fuelled heating (including heat pumps) and non-fossil-fuelled CHP. This top-down approach was found to be useful in identifying areas of high potential, although more focussed studies are required to make accurate assessments.

5. **To assess the historic trends in energy-related GHG emissions and the underlying causes of observed changes.**

   A decomposition analysis of energy-related carbon emissions from 1990-2009 was undertaken in Chapter 5 using an LMDI I methodology. This built on work in Chapter 3 which assessed changes in energy demand, outputs and SEC from 2002-2010. Over 1990-2009 industrial energy-related carbon emissions fell by approximately 3% per annum. The dominant factor in this reduction was found to be a falling energy intensity, indicating improving energy efficiency or intra-sector structural change. Inter-sector structural change was found to cause a slight reduction in energy demand. Changes in fuel mix have increased emissions over the period with shifts to increased electricity use. The emissions factor of electricity has improved however and caused a decrease in carbon emissions over the time period. From 2007 onwards a drop in energy demand was linked to falling production levels, resulting from the post-2008 recession. Prior to this production growth had acted to increase energy demand. There is some evidence from the analysis that, during periods of production growth, energy intensity tends to improve as investment is made in new and improved equipment. Over the period studied, energy prices have been relatively low and are thought to have had little effect on the energy intensity changes. In previous time periods, studies suggest that industry may have exhibited improved intensity in response to a sustained period of high energy prices. However, high energy prices can also constrain growth and limit investment in energy efficient equipment. When the energy-intensive and non-energy-intensive subsectors of industry were examined separately, it was found that the non-energy-intensive subsector made greater relative reductions in energy-related carbon emissions and energy intensity over the period 1990-2009. This was despite notionally weaker drivers to improving energy efficiency. There is evidence that this is due to the energy-intensive subsectors making more substantial improvements over the period from 1973-1990. This has consequently meant that further improvements have been more difficult, with the 'low-hanging fruit' of efficiency improvements having already been 'picked' in the energy-intensive subsector. In contrast in the non-energy-intensive subsector, realisable improvements have more easily been available over the period 1990-2009.

6. **To perform a detailed study of technologies that have wide application and promising prospects for improving energy efficiency.**

   This objective was principally met by the assessment of technologies that can exploit surplus heat in Chapter 6. Previous work, based on the dataset introduced in Chapter 3, identified a significant potential of technically recoverable waste heat from sites included in the EU ETS. The work in Chapter 6 assessed the potential for a number of technologies in utilising this waste heat. The potential for recovering heat for reuse on-site was estimated as 15-26PJ/yr, the majority of this potential was for reuse at less than 100°C, this would lead to increased costs compared to recovery opportunities at higher temperatures, and is one reason that this potential is not currently realised. There was potential to recover 29-64PJ/yr of heat to generate 6.7-14.0PJ/yr of electricity using heat-to-power technology. A combination of organic and water based Rankine cycles were proposed for this purpose. Further development of these technologies in waste heat-to-power applications could facilitate their adoption. The potential to transport heat from one industrial site to fulfil demand on another site was estimated at 23.4PJ/yr of heat recovered to supply 11.7PJ/yr (within a 10km transportation distance, with a 50% transportation efficiency). The recovered heat potential increased if greater transportation distances were possible. The existence of heat networks within the UK would make this opportunity viable. Smaller potentials for heat recovery were also identified in providing a chilling demand through absorption chiller technology and using heat pumps to upgrade the available heat to higher temperature levels. When evaluating combinations of technologies on-site recovery, and heat-to-power options displayed the maximum potentials. Such a combination of technologies was estimated to have the potential to save around 2.4MtCO_{2e}/yr.

7. **To examine subsectors of industry in terms of specific prospects for improving efficiency.**

   The Food and drink and Cement subsectors were assessed in terms of their improvement potential in Chapter 7. Due to the difference in the characteristics of these subsectors, the approach used to evaluate each subsector differed. The Food and drink subsector showed highly varied energy use throughout the subsector, and so the principal energy demand for low temperature heat was focussed on. In contrast, the Cement subsector was found to be dominated by energy use and emissions from the kiln, this therefore formed an obvious focal point for analysis. In the Food and drink subsector savings opportunities through steam system efficiency improvements, increased use of CHP, and heat pumps were assessed. Similar emissions savings were available through the application of each of these options (approximately 500-800ktCO_{2e}/yr, or 10-15PJ/yr in primary energy terms, although the different measures could not be used in fulfilling the same demand). In the Cement subsector efficiency options assessed were a switch to best-available-technology (BAT), the use of waste heat-to-power technology, and clinker substitution. Similar energy savings were offered through clinker substitution and switching to BAT (approximately 4PJ/yr), whilst waste heat-to-power opportunities offered reduced savings (approximately 2PJ/yr of primary energy). In terms of emissions the greatest savings were offered through clinker substitution (approximately 900ktCO_2/yr). Longer term opportunities in cement manufacturing may arise through more radical process changes, fuel switching, and CCS. The Cement subsector offered similar relative savings to the Food and drink subsector.

8. **To combine different studies and approaches to assess the overall prospects for improved energy efficiency in manufacturing. Also to assess the different approaches in achieving this objective.**

   Chapter 8 fulfilled this objective. Opportunities that are available throughout the industrial sector include efficiency improvements in commonly utilised equipment, specifically motor systems and steam systems, which are often immediately available and economic. The increased use of CHP and waste heat recovery are also available throughout much of industry. The methodology for assessing improvement potential can be broadly split between the energy-intensive and non-energy-intensive subsectors. Due to differences in data availability, and the characteristics of the processes utilised within the subsectors, the energy-intensive subsector is best suited to bottom-up assessment, whilst the non-energy-intensive subsector is best suited to top-down studies. Within the non-energy-intensive subsector low temperature heating dominates energy demand. Opportunities additional to those discussed above for the whole sector include fuel switching (dependent on availability to biomass, hydrogen or decarbonised electricity), alongside the use of heat pumps. In the energy-intensive subsector, these low temperature opportunities are likely to have a smaller relative effect. Longer-term improvement potential may involve radical process efficiency improvements and CCS.

   The work undertaken here can be extended and complemented with additional assessment techniques. The influence of other areas of the production chain on the industrial sector, strategies to alter product demand, the extension of the work to other nations, and the use of techniques that consider non-technical solutions to energy demand reduction could be examined.

9.3 STATEMENT OF CONTRIBUTION TO KNOWLEDGE

Here the main contributions to knowledge are outlined, each adds to the understanding of energy use within the UK industrial sector, and its improvement potential, in a unique and valuable manner. To the author's knowledge these contributions have not been published by others.

- Chapter 3 performed a thermodynamic (energy and exergy) analysis of the industrial sector, based on a database constructed utilising information from the EU ETS. This database allowed a more detailed analysis to be performed than previous studies.
- A review and discussion of UK energy policy, as it influences the drivers and barriers identified to the adoption of energy efficient technology, was undertaken in Chapter 4.
- In Chapter 4 the UK industrial sector was split into an energy-intensive and non-energy-intensive subsector, based on clear quantitative criteria. These were designed to represent the strength of drivers to energy efficiency.
- In Chapter 5 a LMDI I decomposition analysis of energy-related carbon emissions in UK industry was reported between 1990 and 2009. Further the energy-intensive and non-energy-intensive industries were examined separately, and reasons for their different results investigated.
- Chapter 6 performed an analysis of the potential for waste heat recovery technologies, throughout the sites of the UK industrial sector involved in the EU ETS.
- Chapter 7 described the use of energy analysis and decomposition analysis to inform, and then undertake, an analysis of energy saving opportunities in the UK Food and drink and Cement subsectors. The prospects for the two subsectors were contrasted.
- A generalisation of the studies performed in this thesis in Chapter 8 allowed findings to be applied to the prospects for improved energy efficiency throughout the UK industrial sector.

9.4 RECOMMENDATIONS FOR FUTURE WORK

In undertaking the present work a number of ideas for further research have arisen. They are briefly discussed here:

- Not all subsectors of industry were studied in detail here. In particular bottom-up studies of energy-intensive subsectors would be valuable additions to the work.
- More focussed studies on a number of improvement potentials identified here could be undertaken. For example, there are opportunities identified in the current work for CHP, waste heat recovery and heat pumps. These could each be used to fulfil a low temperature heat demand. In comparing the different options the technical and economic aspects could be considered alongside wider drivers and barriers. Site level case studies could also form an important component of this work, and be used to compare these opportunities alongside other efficiency measures, such as high efficiency steam systems.
- An extension of the database built from the site level emissions data reported under the EU ETS to cover other sites, and to update this to more recent time periods would be valuable. This could feed into an updated and extended assessment of waste heat recovery opportunities.
- Linking the estimation of waste heat recovery potentials to demands within the domestic and commercial sectors, to identify areas where industrial surplus heat could contribute to a district heating network would be valuable. As part of this, temporal aspects could be considered in greater detail and heat storage methods included in the analysis if appropriate.
- Undertaking a decomposition analysis based on information from input-output tables using 'Structural Decomposition Analysis' could be contrasted to the results presented here based on 'Index Decomposition Analysis'.
- Quantifying any potential 'rebound effect' of increased energy efficiency within the industrial sector would be a valuable contribution. This would include its effect on other sectors of the economy and other nations, but the inherent difficulties in measuring such an effect are recognised.
- To examine longer-term improvement potential within the industrial sector and specifically what affect the uncertainty surrounding the possibility of decarbonised electricity, CCS, biomass and waste fuel would have in defining likely scenarios.
- Extending the analysis of energy efficiency options to compare with other options to reduce energy use and greenhouse gas emissions, such as dematerialisation. How these options applied together would create synergies and conflicts would be of interest.
- Applying the findings of this thesis outside the UK to assess the applicability of the options identified globally.

9.5 CLOSING STATEMENT

This work has quantified the energy use and improvement potential within the UK industrial sector. The thesis has taken the form of a number of separate but interlinked studies. This approach was due primarily to the high variability seen in energy use throughout the sector. Top-down studies were used to assess current energy use, and the potential for a number of cross-cutting technologies. The drivers and barriers to improving efficiency were identified, and the underlying reasons for reductions in energy-related carbon emissions over previous time periods analysed. More detailed studies were undertaken to assess waste heat recovery potential, and to examine opportunities within the Food and drink and Cement subsectors. Within the non-energy-intensive subsector of manufacturing opportunities were identified for technologies that supply low temperature heat. Energy-intensive manufacturing requires more detailed analysis due to the unique nature of the energy using processes employed. Much of the longer-term potential is this subsector will be dependent on radical changes in these unique processes, or the decarbonisation of energy supply.

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Appendix 1

IRON AND STEEL SUBSECTOR ENERGY USE

To get a full representation of energy use in the iron and steel sector the measurement of energy demand needs to go beyond that listed under the 'Final consumption' heading of DUKES. Both blast furnaces and coke manufacture exist primarily as part of the iron and steel manufacturing sector but are listed under the transformation and energy industry use sectors in the aggregate energy balance of DUKES (DECC 2009b), this is as a part of their output is utilised as fuel.

Blast furnaces are an integral part of the iron and steel manufacturing process. Blast furnaces conduct the smelting process that reduces iron ore and exist primarily to undertake this process, with the production of manufactured fuels for other uses a secondary function. Fig. A 1 shows the fuel inputs and outputs of UK blast furnaces in 2007, detailed data for these flows is available in the chapter in DUKES on solid fuels (DECC 2009a). The energy flows shown in Fig. A 1 include fuels converted in the transformation process (shown entering the blast furnace from the left), that are listed under the transformation sector in DUKES and those used to enable the transformation by heating the blast air (shown entering the blast furnace from the top), this energy is listed under energy industry use in DUKES. Blast furnace gas (BFG) is used for recirculation in the blast furnace, coke ovens, other end uses in the iron and steel sector, electricity and heat generation and some is lost in transmission. The values of fuel demand for blast furnaces given in the aggregate energy balances of DUKES (DECC 2009b) are the net demands, where, specifically for manufactured fuels the value given is the result of the inputs shown in Fig. A 1, minus the outputs (the 377ttoe of BFG recycled therefore having zero net effect). This net value is used as the energy demand of blast furnaces for iron and steel manufacture and is added to SIC code 2710 (Manufacture of basic iron and steel and of ferro-alloys) to give a better measurement of energy demand in this sub-sector. When constructing data on energy use all blast furnace demand is assigned to high temperature processing. This is consistent with information on the heat demand of blast furnaces (see Chapter 3).

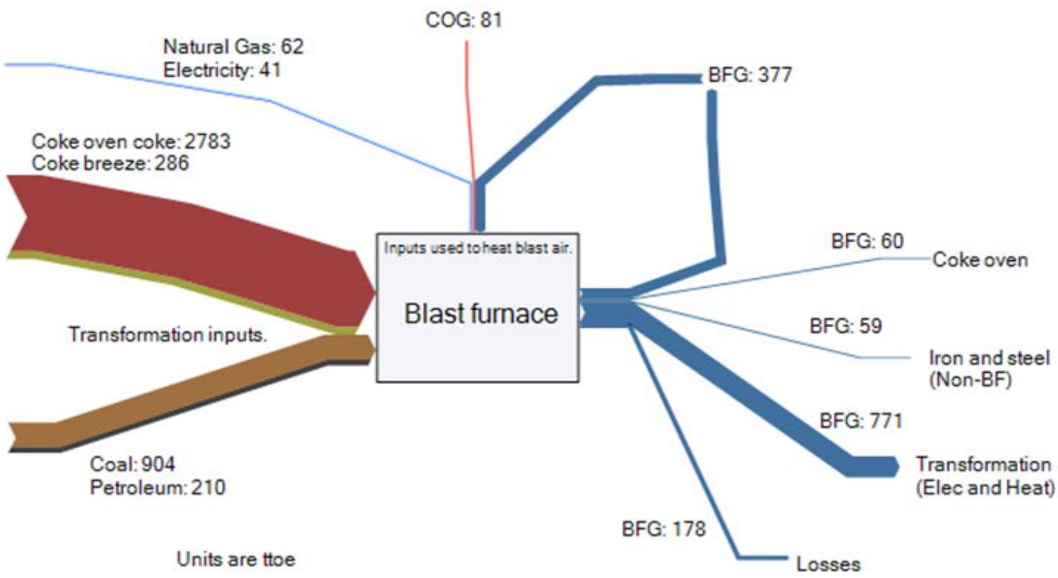

Fig. A 1: Energy flows for blast furnaces: 2007. Data from DUKES (DECC 2009a).

Coke ovens are used to manufacture refined fuel mainly for use in iron and steel manufacture. This is considered to be a fuel refining process as the processing of iron and steel is not undertaken in the coke oven operation. The coke output from the coke ovens that is used within the iron and steel sector is listed within the final energy demand under the manufactured fuels category. No adjustment is made on a final energy demand basis. To account for the energy used in refining the fuel suitable primary energy and GHG emission conversion factors are used.

Manufactured fuel use encompasses a number of refined fuels: manufactured solid fuels, benzole, tars, coke oven gas and blast furnace gas. Within the industrial sector all manufactured fuels are used within the iron and steel sector (or listed as unclassified) (DECC 2010a) with additional manufactured fuel use in blast furnaces and hence assigned to the iron and steel sector, as discussed above. To calculate the primary energy conversion factor and GHG emission factor of manufactured fuels it is assumed that all manufactured fuels come from coke ovens. This is true for the majority of the fuel use and accurate enough for the purposes of the current work. Therefore to calculate the relevant factors information on fuel input and output from DUKES is used (DECC 2010a). In 2009 3,595ttoe of coal and 8ttoe of electricity were used to produce a net output of 3065ttoe of manufactured fuel, using the relevant primary conversion and GHG emission factors for coal and electricity [note a specific figure for the GHG emissions from coking coal was available and was utilised (AEA 2010a)] gives a primary conversion factor of 1.18 and a GHG emissions factor of 111.5 tCO_{2e}/MJ. As the electricity demand is very small in comparison to the coal input separate conversion factors are not required for different time periods.

Appendix 2

DATA COMPARABILITY

There have been several methodological changes within the data available from the Digest of UK Energy Statistics (DUKES) and Energy Consumption in the UK (ECUK) that prevent direct comparisons over the time period in which these changes were made.

- Between 1995 and 1996 there were many methodological differences in DUKES (BERR 1998), meaning data are not directly comparable over this period. Subsectors were affected by differing amounts. As an example in the iron and steel sector since 1996 blast furnace energy use has been listed separately to iron and steel manufacture, previous to this period blast furnace energy use (disregarding coal and coke breeze) was included in the totals for the iron and steel sector. Although this has been corrected for in the data used here (see Appendix 1) data are still not comparable for years before 1995 and after 1996.
- From 1999 onwards heat imported from another subsector is defined as an end-use fuel category in DUKES. Previous to 1999 fuels used to produce heat that was sold to other sectors were included within the final energy demand of the subsector producing the heat. Post 1999 this fuel demand is listed under the 'Transformation' sector. Data pre and post 1999 are not comparable. Heat imported is not listed as a fuel in the disaggregated data available from ECUK, this means the totals for some sectors (primarily Chemicals and 'Other industries') will differ from those shown in DUKES (which are a more complete representation).
- From 2000 onwards the method of collecting natural gas usage data in the iron and steel sector was changed (DECC 2009a), which lead to a reduction in the amount of natural gas usage allocated to the iron and steel sector, with a reallocation of the gas to other sectors. Therefore data before and after this change are not comparable. However this methodological change is not applied to disaggregated data from ECUK until 2001.

When using data from DUKES data should not be compared (or should only be compared with full knowledge of the changes caused by methodological changes) outside of the following time series: 1990-1995, 1996-1998, 1999, 2000-2011. For further disaggregated data from ECUK these time series are 1990-1995, 1996-1998, 1999-2000, 2001-2011.

Appendix 3

SUBSECTOR DISAGGREGATION

The following is a list of the subsector disaggregation utilised in constructing value of production data in real terms, SIC 2003 codes are used. For a small number of subsectors (within 15.8 and 15.9) information was not available to construct the indicator, these subsectors are small and should not have a significant effect on analyses using this data.

- 15.1
- 15.2-3
- 15.4
- 15.5
- 15.6
- 15.7
- 15.81-2
- 15.84
- 15.86,7,9
- 15.91, 7
- 15.96
- 15.98
- 16
- 17.1-3
- 17.4-7
- 18
- 19
- 20
- 21.1
- 21.2
- 22.11
- 22.12
- 22.13
- 22.14-5
- 22.2-22.3
- 24.11-2
- 24.13-4
- 24.15-2
- 24.3
- 24.4
- 24.5
- 24.6-7
- 25.1
- 25.2
- 26.1
- 26.2-3
- 26.4-5
- 26.6-8
- 27
- 28.1
- 28.2-3
- 28.4-5
- 28.6
- 28.7
- 29.1
- 29.2
- 29.3
- 29.4
- 29.5
- 29.6
- 29.7
- 30
- 31.1
- 31.2-3
- 31.4-6
- 32.1
- 32.2
- 32.3
- 33.1
- 33.2-3
- 33.4-5
- 34.1
- 34.2-3
- 35.1
- 35.2
- 35.3
- 35.4-5
- 36.1
- 36.2-3
- 36.4-5
- 36.6
- 37

Appendix 4

TOP DOWN ANALYSIS, ADDITIONAL INFORMATION

Table A 1 presents information on the subsectoral split used in the top-down analysis presented in Chapter 3, for each subsector information of the proportion of electricity demand for heating purposes and the energy efficiency of motor systems is included.

	Proportion of electricity demand used for heat	**Energy efficiency of motor systems**
Aluminium_primary	0.93†	0.46
Cement_dry	0.64	0.60
Cement_wet	0.64	0.60
Ceramics_bricks	0.64	0.60
Chemicals_ammonia	0.00*	0.35
Chemicals_steam cracker	0.00*	0.35
Chemicals_CHP	-	0.35
Chemicals_general	0.18	0.35
Chemicals_carbon black	0.00*	0.35
Chemicals_pharmaceuticals	0.18	0.35
Chemicals_coke	0.00*	0.35
Chemicals_polymers	0.18	0.35
Chemicals_speciality	0.18	0.35
Food and drink_boilers	0.47	0.54
Food and drink_breweries	0.47	0.54
Food and drink_CHP	-	0.54
Food and drink_distilleries	0.47	0.54
Food and drink_maltings	0.47	0.54
Food and drink_sugar beet	0.00*	0.54
Food and drink_sugar cane	0.00*	0.54
Glass_flat	0.00*	0.54
Glass_container	0.00*	0.54
Glass_other	0.00*	0.54
Glass_CHP	-	0.54
Lime_LRK	0.00*	0.60
Lime_PFRK	0.00*	0.60

Lime_MFSK	0.00*	0.60
Semiconductors_boilers	0.24	0.45
Aerospace_CHP	-	0.41
Aerospace_boilers	0.73	0.41
Other_CHP	-	0.45
Automotive_boilers	0.67	0.41
Automotive_CHP	-	0.41
Gypsum	0.64	0.60
Mineral/rock wool	0.00*	0.41
Tobacco_boilers	0.44	0.45
Munitions_boilers	0.67	0.45
Textiles_boilers	0.50	0.41
Tyres_boilers	0.24	0.45
Pulp and paper_boilers	0.62	0.45
Pulp and paper_CHP	-	0.45
Iron and steel_EAF	0.92†	0.29
Iron and Steel_coke ovens	0.00$	0.29
Iron and Steel_sinter plants	0.00$	0.29
Iron and Steel_blast furnace	0.00$	0.29
Iron and Steel_basic oxygen furnace	0.00$	0.29
Iron and Steel_continuous casting	0.00$	0.29
Iron and Steel_mills	0.00$	0.29

Table A 1: Split of subsectors used for disaggregating NAP data, proportion of electricity demand used for heat (DECC 2009d, 2010d), energy efficiency of motor systems (US DOE 2004). †It is known that a much greater proportion of electricity is used for heating than for the parent subsector in ECUK (DECC 2009d, 2010d), hence this figure was calculated using a separate methodology (see below). *A much smaller proportion of energy demand is represented by electricity in comparison to the parent subsector, therefore all electricity demand is assumed to go towards motor systems. $The iron and steel sector fuel split is based on the electricity being for non-heat use at the integrated works (McKenna 2009), hence no electricity demand is assigned to heating processes.

For subsectors for which it was known that the proportion of electricity going to heat was not well represented by the parent subsector in ECUK (namely Aluminium and the Electric Arc Furnace route for producing iron and steel) the figure given in Table A 1 was calculated from information on the proportion of energy going to non-heat uses (DECC 2009d, 2010d) and the proportion of electricity in the fuel split for the subsector (McKenna 2009) using the following formula:

$$E_{th} = 1 - \frac{M}{F_{el}}$$

where E_{th} is the proportion of electricity used for heating processes, M is the proportion of energy going to non-heat (motor system) uses in the parent subsector and F_{el} is the proportion of electricity in the subsector’s fuel split.

Appendix 5

UK POLICY

The main policies that influence energy use and emissions in UK manufacturing are discussed here under the classifications introduced in section 4.2. The list of policies will likely be incomplete due to the wide range of policies in existence, some of which can indirectly affect energy use and emissions. For instance policies that target the energy industry and affect the price paid by industry for fuels and electricity are not covered here. Those that primarily cover the reduction of non-carbon emissions, waste, building energy use, such as lighting, space heating etc. will also not be discussed here, instead the focus will be on those policies that specifically relate to industry and the processes and energy uses specific to this sector.

Cap-and-trade

There are two cap-and-trade systems that affect UK industry, the European Union Emissions Trading System (EU ETS) and the Carbon Reduction Commitment (CRC).

EU ETS

The European Union Emissions Trading System (EU ETS, formerly the European Union Emissions Trading Scheme) is a cap-and-trade system covering emissions from electricity production and energy-intensive industries in EU countries[21]. The EU ETS is the primary policy aimed at curbing emissions from UK manufacturing. The system is divided into three phases, the current, second phase, running from 2008-2012. The first phase covered 2005-2007, with the third phase planned for 2013-2020. For each of these phases the Member States must develop a National Allocation Plan (NAP) which must be approved by the European Commission. These plans set an overall cap on the total amount of emissions allowed from all the installations covered by the scheme in a Member State. This cap is converted to allowances (known as European Union Allowances, or EUAs), where one allowance is equal to one tonne of CO_2. The allowances are then distributed by Member States to installations in the scheme. Installations covered by the Scheme are required to monitor and report their emissions. At the end of each year they are required to surrender allowances to account for their actual emissions. They may use all or part of their allocation and have the flexibility to buy additional allowances or to sell any surplus allowances generated from reducing their emissions below their allocation. In this way the scheme aims to set an overall cap on CO_2 emissions, and provide financial incentives for firms involved in the system to reduce their emissions.

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[21] A United Kingdom Emissions Trading Scheme (UK ETS), similar to the EU ETS (although UK specific) operated from 2002 to 2006. It is not discussed in detail here as it is now closed, although previous participants can still trade allowances as part of the CCAs .

In the UK the EU ETS covers, within the industrial and energy sectors: combustion installations with a rated thermal input capacity of at least 20MW$_{th}$, in addition to refineries, coke ovens and steel plants and installations that exceed a certain production threshold of cement clinker, lime, bricks, glass, or pulp and paper[22]. This coverage represents 100% of power station emissions and 76% of industry (Committee on Climate Change 2008).

To be successful the system relies on the cost of EUAs being high enough to make additional carbon saving measures (such as increased energy efficiency) financially attractive in comparison to emitting at a higher level and purchasing additional permits, this is the area that the EU ETS has come in for most criticism. In the first phase, which ran from 2005 to 2007 there was a large over allocation of permits, to the extent that the permits exceeded the actual emissions and the carbon price hit zero in 2007 when this was realised (Committee on Climate Change 2008). The over allocation was driven by individual Member States over estimating their emissions in order to protect their firms from greater costs in reducing emissions compared to the rest of the EU. This problem has continued somewhat into the second phase, however promisingly when it emerged that the market was again oversupplied due to the recession and slowdown of manufacturing, prices did not collapse, but actually increased slightly (Harvey 2010), indicating companies are taking a longer view (as permits can be used in subsequent years) and were already allowing for this slowdown. However since May 2011 when permits where 17€/t CO_2 prices have fallen to approximately 6€/tCO_2 in April 2012 (European Energy Exchange 2012). This is linked to an EU wide drop in emissions in 2011, with the UK emitting less than its free allocation for the first time during Phase II (ENDS 2012). The Committee on Climate Change (2008) predicts that under an EU target of reducing GHGs by 30% by 2020 the carbon price should reach 51€/t CO_2, this drops to 41€/t CO_2 if the target for 2020 is a 20% reduction in GHGs[23].

The UK has been one of the more ambitious members of the EU ETS so far, in that they received less permits than could cover the 2005 emissions in Phase I (Skjaerseth and Wettestad 2008). In Phase II the UK continued to be ambitious with their plan being the only one to be unconditionally accepted by the central commission. However even if the UK is adopting an ambitious target carbon prices can still be kept low by actions in the rest of the EU. The Carbon Floor Price (CFP) is a proposed policy to set a minimum price for carbon in the UK which the EUAs would not dip below. It was announced in March 2011 and the government's support for the scheme restated in the 2012 budget. A Carbon Price Floor of £16 tonne of carbon dioxide would be adopted in 2013, rising to £30 by 2020 in 2009 prices (parliament.uk 2012). There are fears that as the scheme would only apply to the UK it would harm the competitiveness of UK manufacturing against companies based in other nations (Sinclair 2011). If the CFP caused the likely reduction in UK emissions this would have the knock on effect of reducing EUA prices throughout the rest of Europe and so potentially not lead to emission reductions at an

[22] Full details on inclusion can be found in DEFRA (2007d).

[23] These prices quoted are the central estimates and are dependent on fossil fuel prices and the amount of renewable energy employed.

EU level. These were the finding of the Energy and Climate Change Select Committee (parliament.uk 2012). An EU reduction in the number of permits and so an increase in prices throughout the EU is seen as a preferred method of increasing the effectiveness of the EU ETS (parliament.uk 2012).

Another criticism of the EU ETS has been that, up to this point, allowances have mostly been given free to installations based on historic emissions (known as grandfathering). In sectors where the cost of permits can be reflected in customer prices windfall profits have been made as a result of this free permitting. In the UK power sector these profits were estimated as £1.6 billion annually during Phase II (Committee on Climate Change 2008). It is also argued that grandfathering encourages the continued operation of older, inefficient plants (Clo 2010) and emitting heavily now, in order to obtain more permits in the future. Auctioning has been proposed as a more effective means of allocating allowances, in phase II up to 10% of allowances could be auctioned, the UK chose to auction 7%. For Phase III of the scheme, running from 2013-2020 the proposal was to have full auctioning, the EU Directive (Directive 2003/87/EC) adopted in April 2009 actually includes three different allocation rules. The energy sector will be 100% auctioned (with some exceptions), energy-intensive manufacturing will move from 80% free allowances in 2013 to 30% free allowances in 2020 and full auctioning in 2027. This approach, reducing free allocation and increasing auctioning is a recommendation of a report examining the lessons learnt during the first phase of the scheme (Grubb et al. 2009). Sectors with a high risk of carbon leakage, if their costs are raised significantly, will receive 100% of allowances for free. There is also a move so that free allowance allocations will be based on benchmarking studies rather than historical emissions (HM Government 2009b), this implies that inefficient plants will not receive free allowances to cover all their emissions and so will have to purchase additional allowances or improve efficiency to the benchmark for the sector (Clo 2010). Additionally in Phase III of the scheme rather than the overall EU cap being the sum of the individual NAPs an EU cap will be set centrally and allocated to member states. Another important change will be the inclusion of all metal production and (for some sectors) the inclusion of emissions of GHGs other than CO_2 (Carbon Trust 2010b).

As alluded to above the danger with a high carbon price, if only applied to the EU is that a higher proportion of energy-intensive manufacturing could be moved to outside the EU. This would obviously hurt the economy of the Member States, carbon leakage would also lead to higher overall emissions due to manufacturing in the EU tending to be more efficient than the alternative countries and additional emissions from transport requirements, if products are imported back to the EU. A report by the Carbon Trust on the subject of carbon leakage due to the EU ETS (Carbon Trust 2008), found 90% of UK manufacturing activities would be unaffected by paying for all their allowances. Sectors most in danger of carbon leakage are Lime, Cement, Iron and Steel (via. blast furnaces) and Aluminium (accounting for the indirect costs of allowances for the power producers through higher electricity prices) (Carbon Trust 2010e). Carbon leakage is also seen as more of an environmental than a financial issue, the sectors responsible for 50% of manufacturing's CO_2 emissions only account for 1% of the UK's value added and 0.5% of employment (Carbon Trust 2008). A study by the Carbon Trust (2010e) concluded the risk of carbon leakage does not justify exemption of any sectors from the EU ETS, rather sector specific approaches to the problem of carbon leakage are recommended.

Fig. A 2 shows the cost per kWh supplied by coal, natural gas and electricity. It includes the price paid in the industrial sector for each fuel (DECC 2009f), the CCL and the effect of purchasing EUAs to cover the emissions from using each of the fuel sources at 17€/tCO_2 (the approximate price of an EUA in the final quarter of 2008), using relevant emission factors for the fuels (AEA 2009a). Many sites would not pay the full CCL shown here due to the reduction through belonging to a CCA. Some EUAs would also not be paid for, due to the free allocation of allowances. The EUAs for electricity have to be purchased by the power generators, but the cost is passed onto users. The error bars in Fig. A 2 show the increase in cost if the cost of an EUA rose to 51€/tCO_2, as required for a 30% reduction in GHG emissions by 2020 (see above). The EUAs therefore have the potential to significantly affect the fuel price but require a limit to free allowances and a reasonable price to do so.

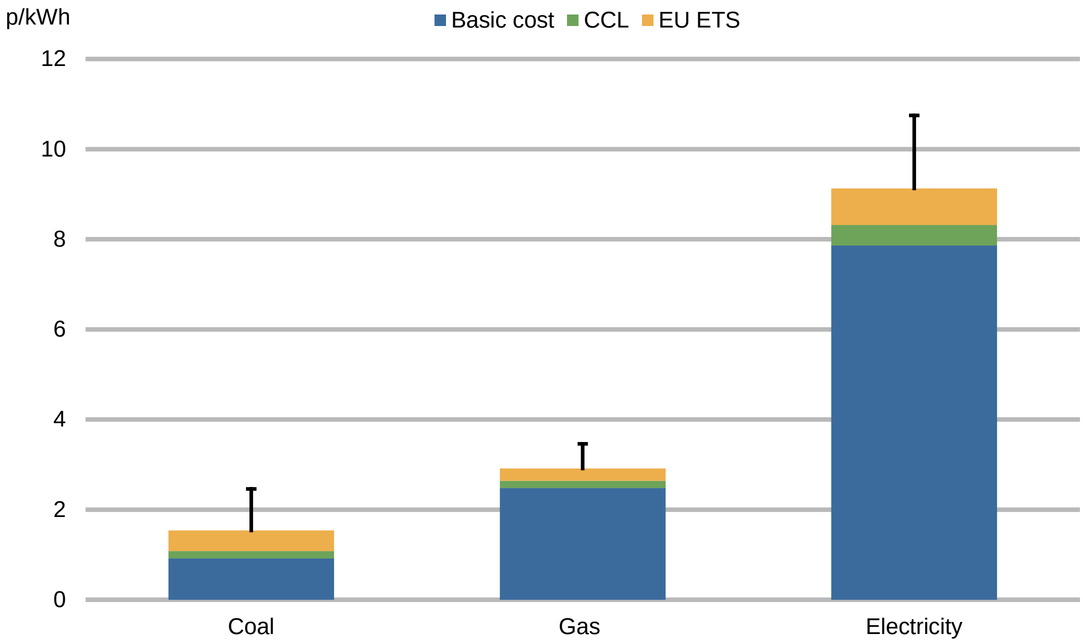

Fig. A 2: Full cost of energy use, including purchase of energy, the CCL and the EU ETS. Data is for the final quarter of 2008 (DECC 2009f), and based on an EUA of 17€.

A recent evidence based review of the effect of the EU ETS on the industrial sector (Martin et al. 2012) found *'no robust or precise estimate of the policy's specific effect on the industrial sector'* in regards to emission abatement. Additionally there was no compelling evidence that competitiveness of those companies involved in the system was adversely affected, and no strong evidence that the EU ETS was driving low carbon innovation in those firms involved in the scheme. Overall significant gaps in the literature linking evidence to effect for the EU ETS were identified (Martin et al. 2012). This does not necessarily mean that the EU ETS is not having a positive effect on energy efficiency in the industrial sector but that further evidence of its effect is required. Careful control of the free allowances and the price of allowances could increase the effect of the EU ETS. At the EU level the EU ETS cut emissions by an estimated 120-300MtCO_2 in the first phase according to one study, this was up to 5% of the emissions of the industries involved (Grubb et al. 2009). Costs were found to be less than projected, a small fraction of 1% of EU GDP (Grubb et al. 2009). It is thought that costs could be eliminated, or the scheme have a positive economic impact if auction revenue is used appropriately. It was also found that all industrial sectors partaking in the EU ETS had profited in the first phase (Grubb et al. 2009). Whether this will continue with subsequent tightening is questionable.

The CRC Energy Efficiency Scheme

The CRC Energy Efficiency Scheme (formerly the Carbon Reduction Commitment) widens climate change legislation beyond those businesses involved in the EU ETS or Climate Change Agreements. Within industry the CRC targets large non-intensive companies, it also covers businesses that are large energy users and public service organisations, and so also applies, for example, to banks and universities. Entry to the scheme is based on electricity use (greater than 6000 MWh/yr based on half hourly metered use), this is based on the company's energy use, rather than that of an individual site. It also covers all energy end use emissions, it should cover between three and four thousand organisations (BERR 2008b). The scheme started in April 2010 with an introductory period during which organisations calculated their energy use, allowances were sold at a fixed price of £12/tCO_2, from April 2011 (Carbon Trust 2010a). From 2013 onwards the CRC will be a 'cap-and-trade' scheme, similar to the EU ETS, with allowances sold at auction and the total amount of allowances decreasing with each year. Links to the EU ETS will be fostered with CRC participants able to purchase allowances at the higher of the EU ETS price or CRC floor price. It was originally planned that revenue from the CRC will be returned to participants based on performance in reducing emissions through energy use. The scheme would therefore offers financial incentives, however this has since been revised (Elliott and Jowit 2010) with the government retaining the revenue from the scheme. It is thought that the CRC may have similar effects to the CCAs (see Chapter 4) in drawing attention to energy and carbon related issues. The recent budget in March 2012 heavily criticised the CRC, referring to it as being *'…cumbersome, bureaucratic and imposes unnecessary costs on business,'* (The Guardian 2012) the scheme will likely be replaced with an environmental tax unless administrative costs can be cut. A consultation was launched by DECC on the simplification of the scheme (DECC 2012a).

Carbon tax

Climate Change Levy

The Climate Change Levy (CCL) is a tax on non-household energy use of coal, gas, electricity, and non-transport LPG. Whilst it does not directly tax carbon it does tax carbon intensive energy sources. The CCL started on 1st April 2001 and led to an average increase in the price of coal by 6.8%, electricity by 2.8% and gas by 1.9% in the fourth quarter of 2008 (DECC 2009e). The effect of the Levy in 2008 can be seen in Fig. A-3. The Levy was coupled with a cut in employers' National Insurance contribution, so that overall taxation was not increased, but energy efficiency was rewarded. Fig. A 3 shows average energy price for the industrial sector with two lines for each fuel from 2001 representing the price with and without the CCL. It can be seen that the CCL only has a small effect compared to price fluctuations. It was found by the National Audit Office (2007) that the Levy had the effect of increasing awareness of energy efficiency upon its announcement in 1999 (in both energy-intensive and non-energy-intensive manufacturing) and this raising of awareness has remained, however the Levy is not seen as a key driver to increasing energy efficiency based on survey (results from 2007), due to its small effect on price. In 2010 saving due to the Levy are estimated in the order of 3.5MtC (12.8MtCO_2) annually (National Audit Office 2007).

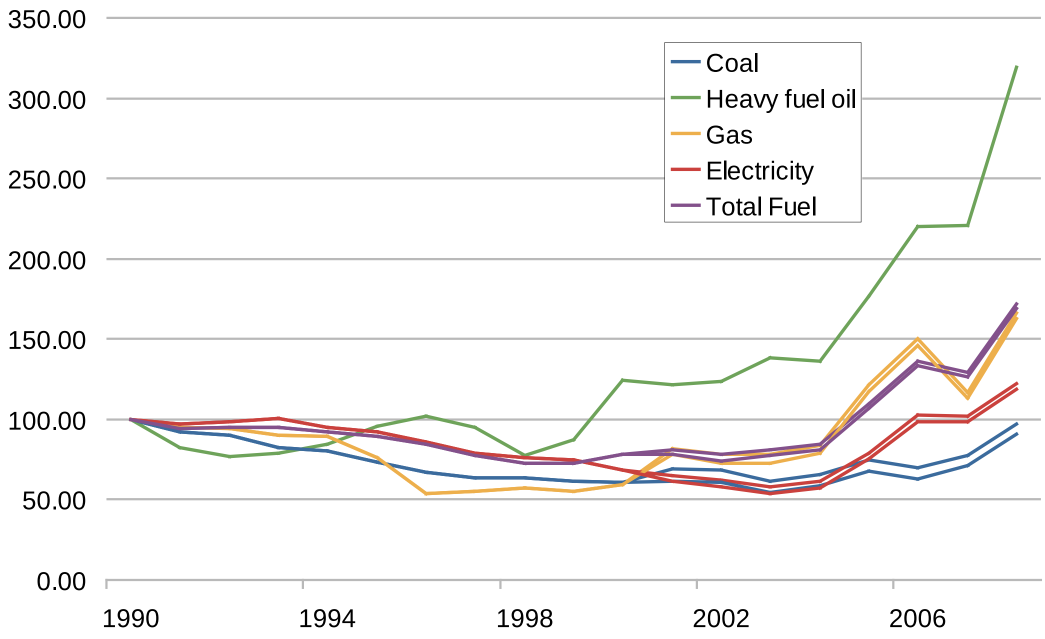

Fig. A 3: Industrial sector fuel price indices in real terms, 1990-2008. From 2001 the two lines for each fuel show the effect of the CCL. Data from Department of Energy and Climate Change (2009g)

Climate Change Agreements

The Climate Change Agreements (CCAs) give energy intensive industries an 80% discount on the CCL in return for reducing emissions, usually through targets regarding the specific energy consumption (SEC) of subsectors. There are ten major energy intensive sectors and over thirty smaller sectors with agreements, the ten major energy intensive sectors are:

- Aluminium
- Cement
- Ceramics
- Chemicals
- Food and drink

- Foundries
- Glass
- Non-ferrous metals
- Paper
- Steel

The agreements are voluntary, to claim the reduction businesses have to reach a target milestone negotiated from a sector specific baseline, the targets are designed to be challenging but cost effective for the businesses involved, so they do not lead to carbon leakage. The CCAs are negotiated through 2013, and are intended to extend to 2023. The savings derived from the CCAs were estimated at 1.9MtC/yr (7.0MtCO_2) in 2010 (National Audit Office 2007), although the Association for the Conservation of Energy concluded that compared to what would be expected under a business as usual scenario the CCAs made little if any increases in energy efficiency (Ekins and Etheridge 2006). As discussed in section 4.2.1 the CCAs may have had a substantial awareness effect however.

Subsidies and loans

The Green Investment Bank (GIB) is a government scheme designed to fund 'green' energy projects. Of interest to the manufacturing sector are support for waste schemes (increasing recycling or use as fuel), and non-domestic energy efficiency projects. At the time of writing (April 2012) the GIB is yet to receive full approval, but from April 2012 the government will be supporting projects on commercial terms, this will include waste projects and infrastructure related efficiency projects (BIS 2012b).

The Carbon Trust was set up by the UK government, in 2001, alongside the CCL. It is a private sector company delivering a public service and has not-for-dividend status (reinvesting any profits). The Trust's stated mission is to *'accelerate the move to a low carbon economy'*. It provides support to businesses and the public sector in cutting emissions. This support comes in the form of financial assistance and information in relation to the manufacturing sector (Carbon Trust 2010d). The Carbon Trust offers interest free loans to energy conservation projects, and enhanced capital allowances (ECAs), that provide tax relief for the year of purchase on a range of energy efficient technologies.

Industry is the primary user of CHP so policies targeting CHP act significantly to increase efficiency in the industrial sector. 53% of CHP electric capacity is within the industrial sector (DECC 2010b). CHP is supported in a number of ways by policy, to gain this support it must be Good Quality Combined Heat and Power (GQCHP), meaning it operates at a high efficiency, guidelines for Good Quality are set down in the EU CHP Cogeneration Directive (2004/8/EC). Fiscal incentives such as exemption from the CCL (recently extended to 2023) and eligibility for ECAs, are combined with grants and favourable regulatory frameworks to encourage the uptake of CHP.

The Renewable Heat Incentive (RHI) provides financial support to renewable heat generation. The scheme has been open for applications since November 2011(DECC

2011e). It covers, biomass boilers and CHP, solar thermal, ground and water source heat pumps, biogas production, geothermal, energy from municipal solid waste and the injection of biomethane into the grid (DECC 2011e). Projects that qualify will receive an income stream for twenty years for the renewable heat generated, the tariff is dependent on the type of technology installed (DECC 2011e). There has been some criticism levelled at the RHI, for causing policy conflicts and for not supporting fossil fuelled CHP, reuse of surplus heat from industry and district heat networks (Hubert 2010). Also the RHI currently only supports those projects that produce hot water or steam, as these can be easily measured (DECC 2012h). Technologies that directly heat air are being considered for inclusion.

Regulation

Due to the variability of the processes used in industry it is difficult to regulate efficiency through much of manufacturing. However there are certain technologies that do lend themselves to this regulatory approach. Motors, boilers, lighting, compressors, and refrigeration would be suitable for regulation in some form. Mandatory efficiency performance standards (MEPS) have been shown to have a strong effect in the use of motors. In the US and Canada, where MEPS have been in existence for some time the proportion of high efficiency motors is around 70%, in the EU, where standards are not mandatory more than 90% of motors operate at or below standard efficiency (IEA 2007). The lack of standards for boilers in the industrial sector (Future Energy Solutions 2005a) is also an area that could be improved. There have been some moves to establish energy efficiency standards (European Commission 2005, 2006a), but these remain as proposals rather than specifying requirements.

Information

The Carbon Trust provides a hub for a range of information services to businesses, this includes (Carbon Trust 2010d):

- Carbon surveys (energy audits) for companies with an energy bill exceeding £50k/annum.
- Sector and technology specific advice in the form of freely available publications. As well as general publications on saving carbon.
- Online carbon management training.
- Telephone support for carbon reductions.
- Advice on energy management.
- Free materials for promoting energy efficiency throughout organisations.
- Carbon footprinting tools and standards.
- Enhanced Capital Allowances (ECAs) provide tax relief for the year of purchase on a range of energy efficient technologies.

- The Carbon Trust Standard that recognises real reductions in carbon emissions, in an attempt to curb the 'greenwash' used by some companies in claiming an environmentally friendly image.

It is expected that the Trust will reach its target for emissions reductions of 4.4MtCO_2 per year by 2010, this is quite small in comparison to the overall target for business of 32 MtCO_2 (House of Commons Committee of Public Accounts 2008), and is smaller than the contributions from the CCAs and CCL. Due to EU laws on State Aid (prohibiting giving aid where it has the potential to distort competition) the Carbon Trust has been unable to target specific organisations that are heavy emitters of carbon, this has restricted its possible effectiveness (House of Commons Committee of Public Accounts 2008). In 2011 the Trust's funding was cut by 40% (Carrington 2011).

Trade associations often provide members with information on reducing their energy use and emissions. Government run organisations such as Envirowise, Business Link and the Waste and Resources Action Programme (WRAP) provide sources of information for companies looking to improve efficiency (HM Government 2009b).

The Integrated Pollution Prevention and Control (IPPC) Directive has existed since 1996, became an EU Directive (2008/1/EC) in 2008 and aims to minimise pollution from industrial sources throughout the EU. It is due to be replaced by the Industrial Emissions Directive in 2013. Operators of installations that are high emitters of pollution are required to obtain environmental permits from the authority in their country of operation, this covers 52,000 installations in the EU, in the UK the regulating authority is the Environment Agency (EA). It regulates energy use and emissions along with raw material used, waste, operating techniques and technologies, and accident prevention, it aims to take into account all aspects of an installation's environmental performance in providing a permit. As part of the Directive documents on Best Available Techniques (BATs) have been produced for the industries covered, these are a useful resource.

Appendix 6

PUBLISHED PAPER REPRODUCTIONS

The following papers are reproduced in the Appendix with the publishers' permission and the copyright rests with the publishers'. They each relate to work presented in this thesis. They are presented here in chronological order. The current author was lead author for the first, third and fifth paper. The order of authors in each case is alphabetical:

If this thesis was accessed online the paper reproductions will not be available. They can be accessed through the publishers' websites.

Hammond, G.P., McKenna, R.C. and Norman, J.B., 2009. Thermodynamic Analysis of the UK Industrial Sector. *Proceedings of Fifth European Conference on Economics and Management of Energy in Industry (ECEMEI-5),* Vilamoura, Portugal. Rio Tinto, Portugal: Cenertec.

McKenna, R.C. and Norman, J.B., 2010. Spatial modelling of industrial heat loads and recovery potentials in the UK. *Energy Policy,* 38 (10)**,** pp. 5878-5891.

A concise revision of a report for the Energy Technologies Institute in 2009

Hammond, G.P. and Norman, J.B., 2012. Decomposition analysis of energy-related carbon emissions from UK manufacturing. *Energy,* 41 (1)**,** pp. 220-227.

A revised and extended version of a paper originally presented at the *23rd International Conference on Efficiency, Cost, Optimisation, Simulation and Environmental Impact of Energy Systems (ECOS 2010)*, Lausanne, Switzerland.

Griffin, P.W., Hammond, G.P., Ng, K.R. and Norman, J.B., 2012. Impact review of past UK public industrial energy efficiency RD&D programmes. *Energy Conversion and Management,* 60**,** pp. 243-250.

A revised and extended version of a paper originally presented at the *24th International Conference on Efficiency, Cost, Optimisation, Simulation and Environmental Impact of Energy Systems (ECOS 2011)*, Novi Sad, Serbia.

Hammond, G.P. and Norman, J.B., 2012. Heat recovery opportunities in UK manufacturing. *International Conference on Applied Energy (ICAE 2012).* Suzhou, China.